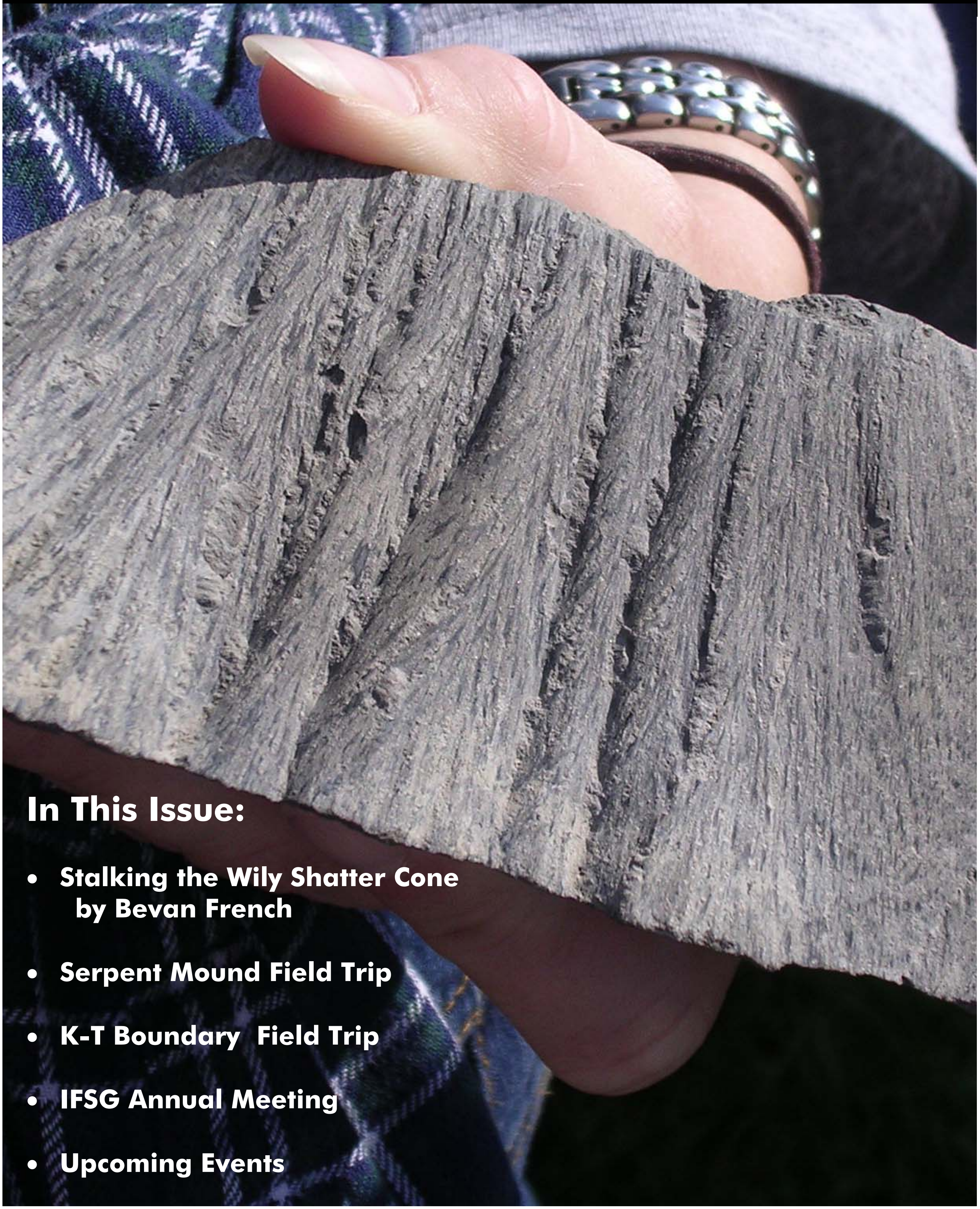
Impacts in the Field

Vol. 2. Winter 2005 A Publication of the Impact Field Studies Group



In This Issue:

Impacts in the Field is a quarterly publication of the Impact Field Studies Group (IFSG). The IFSG brings together widely-separated researchers doing work at a variety of impact crater locations to share their observations and field experience for the common good of the impact community. The IFSG is dedicated to: (1) facilitating discussion of field-based impact geology, (2) gaining additional expertise by facilitating visits to confirmed/suspected impact sites, and (3) offering field work opportunities to students in planetary science. Membership is open to students, faculty, and researchers interested in or who are actively conducting field-based research. For more information on becoming an IFSG member, visit the IFSG website at: http://web.eps.utk.edu/ifsg.htm.

Editorial Staff:

Keith A. Milam	Editor
Dallas Abbott	Asst. Editor
Bill Deane	Asst. Editor
Gordon Osinski	New Articles

IFSG Staff:

Keith A. Milam	Coordinator
Bill Deane	Webmaster
Andy Winslow	Field Trip Coord.

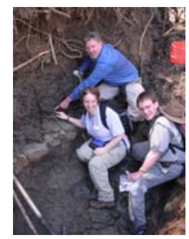
Front cover photo: Shatter cones in carbonate rocks from the Kentland impact structure, Kentland, Indiana. Photo courtesy of Keith Milam, October, 2004.

Impacts in the Field

Vol. 2 Winter 2005 A Publication of the Impact Field Studies Group

Featured Article

Recent Events



Regular Features

Upcoming Events

STALKING THE WILY SHATTER CONE:

A Critical Guide for Impact-Crater Hunters

Bevan M. French
Smithsonian Institution

Finding new meteorite impact craters is both good science and good fun. Several hundred preserved impact craters remain to be discovered on the earth, and you can definitely identify one of them with some lucky sample collection and a little careful work. Such a discovery is worth at least a short note in a peer-reviewed journal. There may be even larger consequences: depending on the size, location, and age of the crater, your discovery might make a major contribution to understanding geological history or the causes of major extinctions. You might generate lively and healthy scientific controversy, attract major media attention, and even become a strong candidate for future funding.

But these positive benefits are balanced by dangers and temptations: wishful thinking, hasty work, and the urge to interpret ambiguous features as evidence of impact when hard evidence is weak or absent. Both past and present literature are littered with controversial impact-crater identifications based on scanty evidence, inadequate self-criticism, and sketchy peer review. In too many cases, the actual observations have been submerged in argument, and media attention has been substituted for critical examination of the data. You want to stay clear of such arguments, and you don't want to increase the amount of bad or ambiguous information floating around. In finding impact craters, you want to be clear, you want your evidence to stand up, and you want to insure that your work is durable.

In hunting impact craters, it is essential to remember a few general rules (and repeat them frequently to yourself): (1) most rocks on Earth have never been involved in a meteorite impact: (2) even in impact structures, most of the rocks will not look shocked; (3) no matter how impressive a structure may look visually or in remote-sensing data, definite and unquestionable impact-produced features will only be found in the rocks; you have to get down on the ground and root around.

Impact-crater hunters have one great geological advantage: large meteorite impacts generate intense shock waves in the target rocks, and these shock waves create unique conditions far outside those of normal geological processes (i.e. transient pressures greater than 10 GPa, temperatures in excess of 2000°C, and strain rates that are orders of magnitude greater than those achieved in normal crustal deformation). These conditions produce unique macroscopic and microscopic deformation features in the target rocks, and these features are diagnostic for meteorite impact, even in structures that are old or even metamorphosed. If these features can be found in the rocks of a structure, even in a single small sample, then the structure was formed an impact event --- period --- and any subsequent efforts should be aimed at exploring the details.

This article has two goals: (1) to describe a group of geological features that are unique, convincing, and generally accepted indicators of shock and impact; (2) to provide skeptical words about other features that may be impact-produced, but which can't be used as impact evidence because they are also formed by normal geological processes. These various features are collected in three sections: (1) Definitely YES (features that are unique and unquestioned evidence of impact); (2) Definitely MAYBE (common impact-produced features that are not unique because they also form in normal geological processes; (3) Definitely MAYBE NOT (features that are probably not impact-produced, and for which even more skepticism is required).

This is a relatively brief and personal view; many details and complications have been left out, and other impact geologists may have different emphases. If you are going to hunt craters, don't rely on this article alone. Go and learn the details from review articles [1 -7], and then try to keep up with the rapidly expanding current literature.

DEFINITELY YES

Several deformational features, both megascopic and microscopic, are unique indicators of shock waves and therefore of meteorite impact. The most commonly-used impact indicators have been shatter cones in the rocks of impact structures and planar deformation features (PDFs) in grains of quartz in the target rocks.

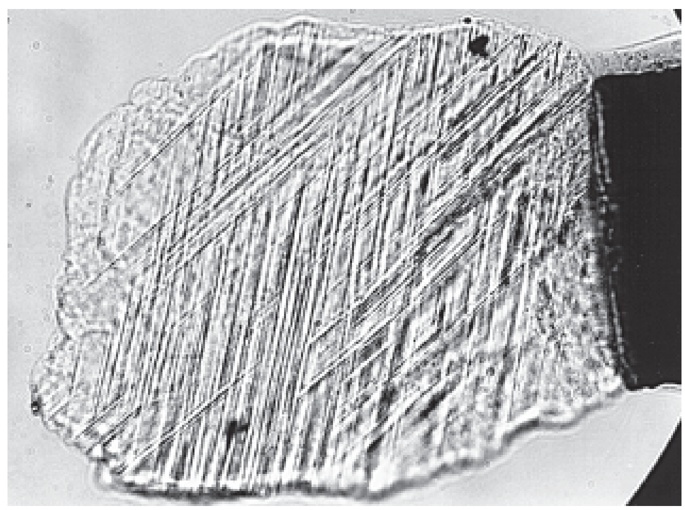
Shatter cones in fine-grained limestone from the Haughton impact structure. Photo courtesy of R. A. F. Grieve

Shatter cones are the only known megascopic (outcrop and hand-specimen scale) feature accepted as evidence of impact. Ideally, they occur as distinctive multiple sets of curved and striated fractures that form cones or partial cones and penetrate large volumes of target rocks in impact structures. Shatter cones, even when poorly developed, tend to be directional: the cones generally (but not always) point upward and inward (toward the shock-wave source at the impact point), and the striations radiate backward from the apex of the cone, diverging and multiplying along the cone surface to form a unique texture ("horsetailing").

Well-developed shatter cones are distinctive, impressive, and unique indicators of impact. Less well-developed shatter cones may form nearly-planar striated surfaces which may lack directionality and which may be ambiguous.

Caution! Shatter cones, both good and bad, can resemble other geological features: sedimentary cone-in-cone structures, fault slickenslides, and wind-abrasion features (see e.g. [8] for a recent review). However, shatter cones have distinctive features that help identification. If you are standing on what you think is a shatter-coned outcrop, check the following points: (1) Shatter cones form in all rock types – igneous, sedimentary, and metamorphic. The best shatter cones form in fine-grained rocks --- limestones and shales. Shatter cones in coarser-grained crystalline rocks are cruder and harder to recognize. (2) The orientation of shatter cones depends on their location relative to the center of the impact structure, and they will therefore be oriented at any angle to sedimentary bedding. (3) Shatter cones are penetrative fractures; freshly-broken samples will show shatter-coned interior surfaces. (4) Shatter-cones have positive and negative surfaces; a convex cone may nest snugly within a reversely-striated concave surface. Both positive and negative shatter-cone surfaces will show grooves with positive and negative relief. If you have surfaces that aren't curved, show only a few striations, and have no radiating pattern, then play it safe; don't use such features as an impact indicator.

Shatter cones have been recognized and argued as impact criteria for more than half a century, but their mechanism of formation, and the conditions under which they form, are still not well-established. They apparently form at relatively low shock pressures ($\geq$2 GPa), but may also develop at pressures $\geq$30 GPa. Shatter cones formed at higher pressures ($\geq$10 GPa) in quartz-bearing rocks may also contain distinctive microscopic shock features such as PDFs in quartz.



Small (0.2mm long) quartz grain from the K-T boundary layer in Colorado. Photo courtesy of G. A. Izett.

PDFs are multiple, closely-spaced sets of microscopic parallel planes that form in grains of quartz and other structurally similar minerals (e.g., feldspar) at shock pressures of 10-30 GPa, far above pressures produced by normal geological processes. PDFs, especially in quartz, are the most widely-used microscopic impact criterion. Despite numerous misidentifications and arguments, no definite PDFs have yet been found in quartz from non-impact geological settings.

Quartz is an ideal mineral for detecting and studying PDFs: it is abundant, durable, optically simple, and not easily deformed by normal geological processes. PDFs in quartz occur as multiple thin planes, typically less than a micron thick and spaced only a few microns apart; they have no separate birefringence in polarized light. Fresh PDFs, which are geologically rare, are composed of a glassy phase. Altered PDFs, which are most common in geologically old impact structures, are transformed to arrays of fluid inclusions ("decorated PDFs") which preserve the orientation of the original planes.

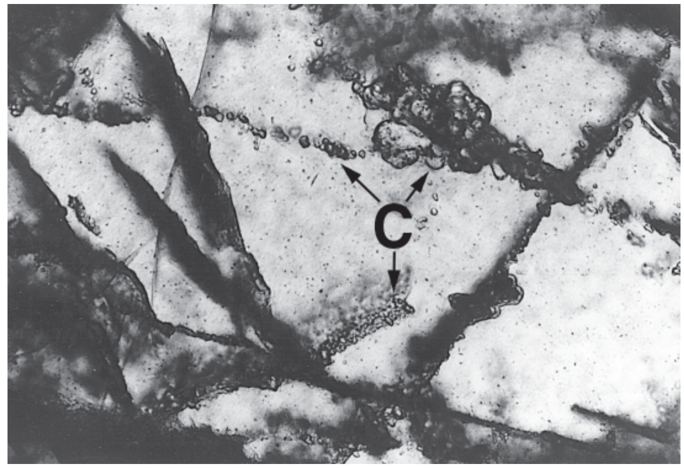
The orientation of PDFs within the quartz crystal lattice is a critical factor in their conclusive identification. Depending on the shock pressure and other factors, PDFs in quartz develop parallel to low-index crystallographic planes such as (0001), $\{10\bar{1}3\}$, and $\{10\bar{1}2\}$. PDF orientations, relative to the quartz c-axis, can be measured with a petrographic microscope, using a standard Universal stage (U-stage) or a spindle stage. The planes can then by identified (indexed) by using a stereographic plot. (For details, see [1,6]).

Caution! PDFs in quartz can be (and often have been) confused with non-impact planar microstructures that form in normal geological processes: deformation lamellae (Böhm lamellae), deformation bands, and subparallel sets of open or healed fractures. For these reasons, orientation measurements of PDFs are critical to their identification. Simple flat-stage photographs of PDFs may be impressive, but the orientation data are needed to establish their nature and origin beyond argument.

If you are faced with possible PDFs, don't be lazy about establishing exactly what they are. Too many recent publications contain photographs of so-called "PDFs" that consist of only a few (often curved) subparallel lines, spaced much more widely than are true PDFs (i.e., >>5µm), and even lacking a scale bar or any other indication of scale. Don't fall into that trap. Describe the features carefully, especially the width of individual planes and the spacing between them. Then find out how to use a U-stage, and go through the small amount of tedious work needed to produce the necessary orientation data. You will be rewarded by producing a data set that is convincing and durable.

High-Pressure (Diaplectic) Glasses.

At higher shock pressures (30-40 GPa), the same minerals that form PDFs (quartz, feldspar, etc.) are entirely converted into glassy phases without going through a normal melting process. The result is a glassy phase (isotropic in polarized light) that is produced by shock (diaplectic glass) rather than by normal thermal melting. This phase retains (pseudomorphs) the original crystal shape and also retains considerable atomic structural order, so that it can be distinguished from both the unaltered mineral and the thermal melt by such analytical methods as refractive index determination, X-Ray Diffraction (XRD), Transmission Electron Microscopy (TEM), and infrared spectroscopy.



Diaplectic quartz glass (clear), with strings of small, high-relief crystals of coesite (C) in suevite breccia from the Ries crater, Germany. Photomicrograph courtesy of W. von Engelhardt (planepolarized light).

Diaplectic feldspar glass (maskelynite) has been known for more than a century in meteorites and more recently from terrestrial impact craters, where it is often accompanied by diaplectic quartz glass. Because of the high shock pressures required to form them, diaplectic glasses are also unique indicators of shock and impact. In practice, diaplectic glasses are less commonly used as an impact indicator than are PDFs. Diaplectic glasses are less abundant in impact craters; because they require higher formation pressures, they tend to develop in a smaller volume of rock closer to the impact point, where the radiating shock waves are more intense. Diaplectic glasses can also be recrystallized (annealed) into briefringent phases whose unique character is not easily recognized. Finally, the process of identifying diaplectic glasses generally requires more sophisticated instruments than are needed for the documentation of PDFs in quartz.

Caution! The presence of apparently glassy (isotropic) material in a thin section is not sufficient evidence for the presence of diaplectic glasses. (A messy and continuing controversy in *Science* about a possible impact structure linked to the Permian-Triassic extinction turns on this very problem.) In a thin section, darkness under crossed Polarized light (isotropism) can be produced by several non-impact conditions: isometric crystal structures (e.g., garnet, fluorite, leucite), microscopic alteration, replacement, or even the fortuitous orientation of an otherwise birefringent mineral grain.

Two steps are needed to establish clearly that a diaplectic glass is present: (1) the chemical composition, determined independently (e.g., by an electron probe) should match that of a mineral (quartz or feldspar) known to form diaplectic glasses; (2) the unique glassy character of the material, and its distinctness from both the original mineral and thermally-melted mineral glass, should be demonstrated by comparative studies using methods that give details about the atomic structure of the various phases, e.g., refractive index measurements, XRD, TEM, infrared spectroscopy, or (possibly) micro-Raman spectroscopy. In the case of diaplectic glasses, simple visual petrographic examination is not enough.

High-Pressure Minerals. The transient high shock pressures associated with impacts also transform minerals in the target rocks into new minerals (polymorphs) that have the same chemical compositions but different crystal structures that are stable at high pressures. These minerals, especially when they are found in sediments or shallow crustal rocks, are also unique indicators of meteorite impact.

Two high-pressure forms of quartz (SiO_2), coesite and stishovite, were used in the 1960s to make some of the first initial identifications of impact structures. Diamond, the high-pressure form of graphite (C), has also been recognized from numerous impact structures, where it has apparently formed from graphite in the target rocks.

Except in rare cases, these high-pressure minerals cannot be identified by simple microscopic observation. More complex operations are generally required: dissolution of rock samples, concentration of the mineral, and identification by XRD, Raman spectroscopy, or some similar method. As a result, these high-pressure minerals are less used for identification than PDFs in quartz, although they remain reliable indicators of impact and are important for understanding the impact process in the target rocks.

Definite Indicators of Impact

- Shatter cones
- Planar Deformation Features
- High-Pressure Diaplectic Glass
- High-Pressure Minerals
- High-Temperature Glasses
- Meteorite Fragments
- Chemical Signatures from the Projectile

Caution! Both coesite and diamond also occur in non-impact geological settings, in deep-seated crustal and mantle rocks (eclogites, kimberlites, etc.) where they have formed in stable equilibrium at the high static pressures present at these great depths. These occurrences can be easily distinguished from impact structures, in which the minerals occur in sediments or shallow crustal rocks, forming disequilibrium textures with other minerals. However, the higher-pressure mineral stishovite has not yet been found anywhere outside of established impact structures.

High-temperature glasses. High-pressure transformations are not the only distinctive effects of impact. High-pressure shock waves (50-100 GPa) generate residual high temperatures (>1500-2000°C) in the rocks through which they pass. Such temperatures are far above those generated in normal crustal processes, and they are sufficient to melt and decompose minerals that are unaffected by lower temperatures. Such melting and decomposition reactions form another group of indicators of shock and meteorite impact.

The melting of quartz (SiO_2) to a glass (lechatelierite) at temperatures above about 1750°C is the most commonly observed mineral transformation at the ultrahigh temperatures produced by impact events. (Keep in mind that lechatelierite is a melted glass, with a different nature and structure than diaplectic quartz glass, which is produced at much lower post-shock temperatures without going through thermal melting.) Other shock-produced transformations observed include the decomposition of zircon ($ZrSiO_4$) to baddeleyite (ZrO_2) (T>1850°C) and the melting of sphene ($CaTiSiO_5$) (T>1400°C). Any of these features are good evidence of impact.

Caution! One rare geological process can generate similar high temperatures in small local areas: lightning strikes that melt near-surface soils and rocks, forming unusual tubular and irregular bodies of heterogeneous glass (fulgurites). If you have nothing to go on but scattered fragments of high-temperature glass, check the geological surroundings and examine the glasses in detail. Look for other evidence of impact, e.g., PDFs in quartz grains in the glass.

Meteorite Fragments. Finding genuine meteorites scattered around a big hole in the ground might seem to be no-brainer evidence that the hole is an impact crater. However, it took several decades before this association was accepted even for Barringer Meteor Crater (Arizona). You will probably not be lucky enough to encounter this association in the field; most of the incoming meteorite projectile is destroyed in the impact, and any surviving fragments weather and disappear quickly. Even if you are lucky enough to find meteorites around a structure, make sure it isn't just coincidence.

Check further. Look for shock features and other definite evidence in the rocks.

Chemical Signatures from the Projectile. Even after meteorite fragments have disappeared, evidence of the impact event may survive in the equally conclusive form of unique chemical signatures produced by material derived from the melted and vaporized projectile and incorporated into the breccias, melt rocks, and ejecta associated with the crater.

The best and most-used signatures in crater rocks are produced by chemical elements that are rare in the Earth's crust (and therefore rare in the target rocks), but enriched in the projectile, so that a small amount of projectile can produce a large chemical anomaly [9]. Siderophiles and related elements are especially suitable for such studies. The element iridium (Ir) is probably the best-known impact indicator because of its importance in recognizing the Cretaceous-Tertiary impact event, but other elements (e.g., Os, Au, Cr) have also been used. In particular, the isotopes of Os have proven to be very sensitive indicators of a projectile component.

Only small amounts of projectile (typically $\leq$1%) are incorporated into the rocks of impact craters. Projectile signatures do not generally occur in the less-shocked and still-in-place target rocks below and around the crater, but tend to occur in the breccias and melt rocks deposited within it. Detecting these small amounts of projectile material requires sophisticated instrumentation (typically Neutron Activation Analysis). (Fortunately, such instruments are common, if not widespread, and you can usually find a collaborator if you have some interesting samples.) Detection thresholds and interpretations vary, but in general, an Ir content of $\geq$1-2 ppb is a strong indicator of a projectile signature and therefore of an impact event.

Caution! Although an Ir anomaly is a good indicator of a projectile signature, that element is also enriched in ultramafic terrestrial rocks, and it can be concentrated by diagenetic processes as well. If an Ir anomaly is found, then both the target rocks and the geological context need to be evaluated to be sure that the Ir is in fact extraterrestrial. In addition, some types of meteorites are not enriched in Ir and related elements, and these will produce no anomaly. Even in definite impact structures, the distribution of chemical signatures is erratic and random. For these reasons, the absence of an Ir anomaly or other chemical signatures is not evidence against an impact origin.

However, the concept of a single "Ir anomaly" as a unique and reliable impact signature, has been much abused, and it is much better not to rely on Ir enrichments alone. Check for enrichments of other siderophile elements, e.g., Co, Ni, Cr, and other platinum group elements (PGEs). If you find enrichments only in one or two, be very skeptical --- you may be dealing with some terrestrial process that can produce selective enrichments. If only Ir (and no other PGEs) are enriched, or the elements are not in the proportions found in chondritic meteorites, you are probably NOT looking at an extraterrestrial signature.

There are other steps that should be taken to be sure than an "Ir anomaly" is really an extraterrestrial signature. The background elemental concentrations in the target rocks need to be determined, so that any local contribution can be excluded. Be aware that there are relatively few laboratories that can produce the necessary precision and accuracy in these analyses. Don't rely on commercial analyses; they may lack the sensitivity needed. Include known standards (known Ir-bearing impactites) with your samples, to be sure that previously determined contents are reproduced in your analyses. If a siderophile enrichment seems to be present, but the data seem contradictory, use a different method as a check, e.g., Os isotopic composition. If you still don't like the data, don't claim that there is an extraterrestrial signature present.

Stick with the siderophile elements and their close friends. Some recent publications have argued that enrichments in other elements such as arsenic and vanadium are characteristic of impact deposits. They aren't. ONLY siderophile elements, and some related isotopic ratios (like Os) are diagnostic for a meteorite component.

DEFINITELY MAYBE:

Another group of deformation features, both megascopic and microscopic, are commonly found in impact structures. They include pseudotachylite breccias, planar fractures (PFs or cleavage) in quartz, and glasses and igneous rocks. Unfortunately, these features can also be produced by normal, non-impact geological processes, and they cannot therefore be used as definite proof of impact. They are most valuable in identifying possible impact sites, indicating where to search for definite shock effects, and (if a positive impact identification can be made) probing the history and mechanisms of how the structure formed. Even though these features may be impressive in outcrop or in thin section, it is a good rule not to rely on them for impact identification, but to use them as a guide to search for more unique indicators.

Pseudotachylites (or Pseudotachylitic Breccias). Many impact structures, especially large ones, display abundant exposures of a striking and unusual rock called pseudotachylite. (The term "pseudotachylitic breccia" is also used. For this article, I keep the simpler term, and the complex terminology will not be discussed further here). Pseudotachylite typically consists of large and small fragments of target rock in a (frequently dark) fine-grained to microcrystalline matrix composed partly or completely of melted and crystallized rock. These breccias generally form veins or large irregular areas in the target rocks below and around impact structures. At Sudbury (Canada) and Vredefort (South Africa) pseudotachylite bodies may be tens to hundreds of meters in size.

The nature and origin of pseudotachylite has been intensely studied and debated ever since the type material at Vredefort was named by S.J. Shand in 1916. In current theories, these breccias are formed by fracturing and frictional melting during large-scale, high-speed displacements that occur during the later stages of crater formation and modification after the main pulse of the shock waves has dissipated. Most pseudotachylites are not part of the high-pressure shock regime, and they only rarely show distinctive shock effects like PDFs in quartz.

However, similar rocks, also produced by friction and also called pseudotachylite, develop during normal geological deformation, especially along major thrust faults. This situation has produced nearly a century of confusion, debate, and argument about the nature, origins, definitions, recognition, and nomenclature of pseudotachylite. At present, it seems increasingly probable that both impact and non-impact pseudotachylites have similar origins (frictional melting during rapid deformation), and it may be impossible to distinguish between the two kinds in hand-specimen or even on outcrop.

This state of affairs means that pseudotachylite cannot be used independently as a unique criterion for impact. However, large deposits of the material, extending over hundreds of meters or even kilometers (as at Sudbury) may be a unique feature of impact structures. Known tectonic pseudotachylites generally occur as veins <1 m across. If you find much larger patches of pseudotachylite, keep looking around for more definite shock effects. (Shatter cones are a common companion of impact-produced pseudotachylite bodies.)

Planar Fractures (PFs) (or Cleavage) in Quartz.

Quartz grains from several established impact structures show multiple parallel sets of open planar fractures (PFs), or cleavages. In these samples, the PFs are a shock effect, probably produced at relatively low shock pressures (about 5-7 GPa), below the levels at which definite PDFs form. The PFs are often associated with definite PDFs, which provide independent evidence of shock and impact in such rocks.

Because cleavage is virtually absent in non-impact quartz, it has been suggested [10] that PFs in quartz, by themselves, might be used as independent criterion for shock and impact. This idea should be applied with caution. There are some reports of cleavage in quartz from non-impact geological occurrences, and cleavage has been produced experimentally in quartz at pressures <3 GPa.

At present, PFs by themselves should not be used as an independent criterion for impact. If quartz PFs are found in a deformed, circular structure, they can be a strong indicator of impact, especially if the off-structure rocks show no deformation [10]. PFs can also indicate where more definite shock features might be found. If you find PFs (even without PDFs) in samples, describe them and measure them carefully; be hopeful, and keep looking.

Glasses and Igneous Rocks.

Impact events can produce high-temperature melting in a large volume of target rock. Much of this impact melt, especially in small, rapidly-cooled bodies, can preserve unique high-temperature melting effects that are definite evidence for impact (see above).

Larger bodies of impact melt, which tend to collect within the crater, may be more ambiguous. Because they, like conventional igneous rocks, are formed by the slow cooling and crystallization of silicate melt, they resemble normal igneous rocks, and they may show no features diagnostic of an impact origin.

Nevertheless, these melt bodies are good hunting grounds for definite impact evidence. They often contain inclusions of target rocks and minerals that show definite shock effects (typically quartz grains with PDFs). They may also contain chemical signatures (e.g., high Ir contents) derived from the projectile. And they may display unusual chemical compositions resulting from unusual target rocks that were incorporated into the impact melt.

DEFINITELY MAYBE NOT

(In Fact Probably Not, at Least by Themselves).

Some impact-produced features are actually far more common in non-impact rocks. They cannot by themselves demonstrate impact, and the odds are that any given occurrence will have a non-impact origin. Such features may be valuable guides for locating definite impact features and for searching for definite shock effects, but definitive impact evidence has to come from something else.

Circular Surface Shape or Circular Deformation Pattern.

Most currently-accepted impact structures were first recognized from a circular shape or as an area of anomalous circular deformation in otherwise undeformed rocks. But a circular pattern is not evidence of impact. There are many non-impact geological features that also produce circular patterns: diatremes, salt domes, calderas, gneiss domes, tectonic cross-folding, and eroded sedimentary uplifts. A circular pattern can only indicate a possible impact site and perhaps point to specific locations for further search and sampling.

Circular Geophysical Anomalies. Many large and small impact structures have definite geophysical anomalies associated with them. Gravity anomalies are generally circular; they tend to be negative over small structures, where impact has produced low-density rocks by brecciation or by filling the crater with post-impact, low-density sediments. (In larger impact structures, this negative gravity anomaly may have a positive anomaly in the center, where deeper and denser crustal target rocks have been uplifted.) Magnetic anomalies associated with impact structures tend to be more irregular and unpredictable.

Even well-developed gravity and magnetic anomalies are not uniquely diagnostic of impact. They can be found associated with a wide variety of more normal geological features. However, like shape and structural deformation, geophysical anomalies are valuable guides to identifying possible impact structures, locating occurrences of distinctively shocked rocks, and probing the two- and three-dimensional character of impact structures once they are established.

Breccias. In most impact structures, the largest volume of impact-produced rocks are breccias, most of which occur beneath and around the crater in the unexcavated target rocks. However, most rocks fracture at low pressures (<2 GPa), and most impact-produced breccias are formed at shock pressures too low (<5-7 GPa) to produce definite impact features. There are dozens of normal geological process --- sedimentary, igneous, and metamorphic --- that can fracture rocks and produce breccias. Breccias, even when found in circular structures, are not evidence of impact. At best, they can be a guide to where to look for better evidence.

Spherules. Spheroidal droplets of melted impact glass are typical products of impact events [11]. Such spherules form from mm-size droplets of melted target rocks. Curiously, spherules are not abundant in impact-produced crater deposits themselves; instead, they tend to be found in thin layers of distal ejecta, which may be deposited hundreds or thousands of km from the impact site itself. (Microtektites, which are spread over continental-size regions of the Earth, are probably the best-known examples of impact spherules.)

Spherules by themselves, however, are not reliable impact criteria, and major problems and controversies have arisen from attempts to use spherules alone as evidence of impact events. Despite the definite association of spherules and impacts, numerous non-impact spheroidal objects are abundant in the geological record: volcanic lapilli, oolites, microfossils, pollen, and fecal pellets, to name just a few. Surface exposures of sediments and spherule layers have also been found to contain a dismaying range and variety of contaminating spheroidal artifacts: arc-welding debris, particles derived from overheated brake linings and catalytic converters, used shotgun pellets, glass beads from reflective highway signs, and other exotics.

An added complication is that even genuine impact spherules tend to occur by themselves and are not accompanied by more definite evidence of impact. (There are some exceptions: the K-T spherule layer contains enhanced Ir values, and at least one microtektite occurrence also contains coesite and lechatelierite.) An additional problem is the difficulty of interpreting spherules in old or metamorphosed rocks, in which the original chemistry may be modified and the original textures and mineralogy are obscured by recrystallization.

Impact-produced spherules can be critically important in impact studies. (For one thing, they can provide evidence about impact structures that have been eroded or destroyed.) But spherules require careful and meticulous work to show that they are (1) natural and (2) impact-produced. Spherule characteristics that can suggest or prove impact include: (1) association with definite impact features, such as lechatelierite or shocked quartz. (2) geologically reasonable chemical compositions corresponding to probable or recognized target rocks, or to known meteorite compositions. (Exotic compositions involving Fe-Ti-S, other rare metals, or hydrocarbons should be regarded with suspicion, and an origin as terrestrial contaminants needs to be rigorously eliminated.) (3) compositions unlike normal volcanic rocks; (4) a lack of association with other volcanic debris (phenocrysts, rock fragments, etc.)

Be tough on yourself (and on other people) before arguing that spherules are impact debris. Unless you can demonstrate that spherules are clearly impact products, because they have lechatelierite (melted quartz glass) or siderophile enrichments (and high Fe contents alone do not qualify), they are probably not impact-derived. Don't add to the accumulated (and wrong) identifications of spherical features produced by volcanoes, bacterial processes, or human activity as impact evidence.

Even with extensive and careful observation, it may not be possible to prove conclusively the impact origin of any given spherule deposit. Debate still continues over the origin of many individual spherule layers, especially those found in Precambrian rocks in Australia and South Africa. If you are faced with a spherule layer, look first for definite impact effects associated with the spherules. If you don't find any, then try at least to eliminate the most common non-impact possibilities.

CONCLUSIONS.

In principle, identifying new impact structures is easy. Look for a circular feature defined by topographic outline, bedrock patterns, intense and localized deformation, or geophysical anomalies. Good sources for finding such potential (or candidate) impact structures are remote-sensing images (both air- and space-based), old geological reports, core repositories, and rumors of odd breccias or strange zones of deformation.

Once you have a target, remember that it is only a possible impact structure. (In fact, most such targets will turn out to be something else or --- more frustratingly --- will yield up neither any clear impact evidence nor any evidence for an alternate origin.) A real impact structure can be definitely identified only from a small number of unique shock effects that can be found only in the rocks in or from the crater: shatter cones, PDFs in shocked quartz, diaplectic glasses, high-pressure minerals, high-temperature reactions, meteorite fragments, or unique chemical signatures in the impact-produced rocks.

It is critical to avoid the danger of proclaiming that you have discovered an impact structure on the basis of features which may have non-impact origins: circular geological features (especially those seen in remote-sensing images), pseudotachylite, slickenslides, brecciation, or non-impact planar microdeformation features (metamorphic deformation lamellae, irregular fractures) in quartz.

Identifying new impact structures involves field work, combined with a certain amount of stubbornness and luck. Patience is also critical: you need to do the routine work of chemical analysis, petrofabric measurements, and data plotting required to establish an impact structure beyond doubt. And you need to be skeptical and critical of your own work at every step of the way. (Experienced colleagues are a great source of valuable criticism.)

With the right combination of luck and persistence, you may not only find impact structures, but you will provide solid and convincing evidence for their existence, as well as a batch of exciting and unexpected results for the future. So take up your hammer, pack an ample supply of skepticism, and head out into the field.

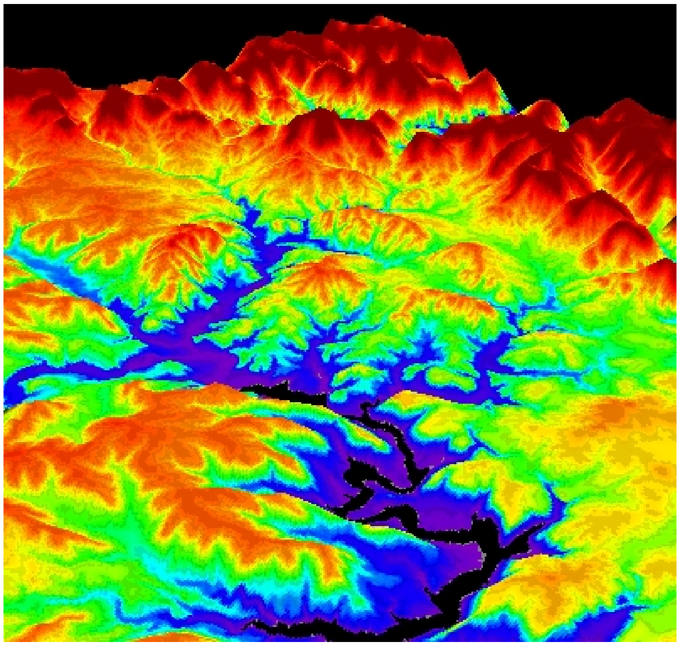
Good hunting!

REFERENCES [1] Stöffler, D., and F. Langenhorst 1994, Science, *29,* 155-181. [2] Grieve, R. A. F. et al., 1996, *Meteoritics and Planetary Science, 31*, 6-35. [3] French, B.M. 1998, Traces of Catastrophe: A handbook of shock-metamorphic effects in terrestrial meteorite impact structures. Houston, TX, Lunar and Planetary Institute, Contribution CB-954, 120 p. [Out of print, but can be downloaded from two web sites: http://www.lpi.usra.edu/publications and http://adsww .harvard. edu.] [4] Grieve, R.A.F., 1997, *Paleogeography, Paleoclimatology, Paleoecology, 132,* 5-23. [5] Koeberl, C., 1997, *In* Johnson, K.S. and Campbell, J.A., editors, *Ames structures in northwest Oklahoma and similar features: Origin and petroleum production (1995 symposium),* Norman, OK, University of Oklahoma Press, pp. 30-54. [6] Montanari, A. and C. Koeberl, 2000, *Impact stratigraphy: The Italian record,* New York, Springer-Verlag, 364 p. [7] French, B.M., 2004, *Meteoritics and Planetary Science, 39,* 169-197. [8] Lugli, S. et al., 2005, *In* Henkel, H. and C. Koeberl, eds., *Impact tectonics,* New York, Springer-Verlag, pp. 87-10. [9] Koeberl, C., 1998, In Grady, M.M., R. Hutchinson, G.J.H. McCall, and D.A. Rothery eds., *Meteorites: Flux with time and impact effects,* London, The Geological Society Publication No. 140, pp. 134-154. [10] French, B.M., 2004, *GSA Bull., 116,* 200-218. [11] Simonson, B.M. and B.P. Glass, 2004, *Ann. Rev. Earth Planet Sci., 32,* 329-361.

Don’t forget!

Go On-line to Check out the Latest News from the IFSG at:

http://web.eps.utk.edu/ifsg.htm



IFSG Field Trip Report: Serpent Mound Impact Structure, Ohio

Members of the Impact Field Studies Group (IFSG), Kentucky Geological Survey, Ohio Geological Survey, Wright State University, Capital University, and the University of Tennessee participated in an IFSG-sponsored field trip to the Serpent Mound impact structure in southern Ohio on October 30, 2004. The Serpent Mound impact crater (not to be confused with the Serpent Mound historical site) is a 256 Ma, 8 km-diameter, complex crater formed in the Paleozoic strata of southeastern Ohio near the junction of Adams, Highland, and Pike counties. The feature was first described by Locke in 1838 [1] and in 1925 W. Bucher proposed it as a cryptovolcanic structure [2]. An impact origin for the Serpent Mound structure confirmed by the discovery of shatter cones [3], coesite [4], and shocked quartz [5].

The field trip began on an overcast Saturday morning at the entrance to the Serpent Mound historical site. Twelve participants were treated to a continental breakfast and a morning briefing by Mark Baranoski of the Ohio Geological Survey, the lead author of the recently published, "Subsurface Geology of the Serpent Mound Disturbance, Adams, Highland, and Pike Counties, Ohio" (2003) [6]. Mark provided an overview of Ohio geology and previewed the Serpent Mound crater, while participants examined ASTER, SRTM, and geologic maps. Mark and his co-author Doyle Watts also provided a historical sketch on early discovery and mapping efforts at this site.

The second stop of the day was at a rare roadcut in what several authors have referred to as the "transition zone", the area between the central uplift and outer ring grabens. The roadcut displayed heavily fractured and locally brecciated rocks.

Next it was off to the outer reaches of the crater along a creek in the southwestern portion of the structure to examine blocks or target rock that collapsed along normal faults during the modification stage of the Serpent Mound impact event.

The third stop was followed by lunch back at the Serpent Mound historical site. There,

Field trip participants examine shatter cones and highly-fractured Ordovician-aged rock in the central uplift of the Serpent Mound impact structure, southern Ohio.

participants had a chance to visit the serpent-shaped mound built by the Adena Indian culture

Carl Petersen of the Kentucky Geological Survey displays his find of shatter cones from the central uplift of the Serpent Mound impact structure, southern Ohio.

from 800 BC – 100 AD. A downpour of rain motivated everyone inside to visit the on-site museum that included viewing of geological, biological, historical, and archaeological exhibits.

In the afternoon, the field trip moved to the center of the structure to examine deformed strata in the central uplift. A long hike over hills and down into gullies revealed disturbed Upper Ordovician-aged strata. Bedding orientations varied widely (ranging to vertical) vertical and rocks were extensively fractured and faulted. A few rare examples of shatter cones were found by Karen Rose Stockstill, an amateur geologist from Sydney, Ohio and Carl Petersen of the Kentucky Geological Survey. At this final stop, Doyle Watts of Wright State University treated us to a poster session on the subsurface seismic and magnetic anomalies of the crater.

Participants examine a geologic map of the Serpent Mound impact at the second stop of the day in the transition zone.

Thanks to all of those who made this field trip possible including Andy Winslow (field trip coordinator), Bill Deane (food), and Mark Baranoski and Doyle Watts for volunteering their time in the field to expose us to their work at the Serpent Mound impact structure. A list of field trip participants follows:

Mark Baranoski	Ohio Geological Survey
Bill Deane	IFSG-Univ. of Tennessee
Terry Lahm	Capital University
Keith Milam	IFSG-Univ. of Tennessee
Kerry Milam	Knoxville, Tennessee
Zacary Mires	Dogwood Elem., Knoxville, TN
Carl Petersen	Kentucky Geological Survey
Karen Rose Stockstill	Sydney, Ohio
Karen Renee Stockstill	University of Tennessee
David Teal	University of Tennessee
Mark Thompson	IFSG-KY Geological Survey
Doyle Watts	Wright State University

REFERENCES [1] Locke, J., 1838, *Ohio Div. of Geol. Survey 2nd Annual Report, 201-286*. [2] Bucher, W. H., 1935, *Compass, 15*, 157-162. [3] Dietz, R. S., 1960 *Science, 131*, 1781-1784. [4] Cohen et al, 1961, *Science, 1343*, 1624-1625. [5] Carlton et al., 1998, *Earth & Planetary Sci. Let., 162*, 172-185.

IFSG Field Trip Report: K-T Boundary Layer along the Brazos River, Falls County, Texas

IFSG members and participants from Brown University, the Canadian Space Agency, the Geoscience & Earth Marine Service, Kentucky Geological Survey, Lamont-Doherty Earth Observatory, Mann Middle School (TX), the Natural History Museum of London, Shell Corporation, University of Houston, University of Pittsburgh, and the University of Western Ontario gathered on Sunday, March 13, 2005 for a day in the field examining the Cretaceous-Tertiary (K-T) boundary layer along the Brazos River, Texas. The field trip was led by Dr. Alan Hildebrand, world-renowned impact geologist and discoverer of the Chicxulub impact, from the University of Calgary.

After a long drive from Houston and through the Marquez Dome impact (last year's field trip site), participants met "in the middle of nowhere" at the intersection of state highway 413 and the Brazos River. Following the morning briefing, the group climbed down the banks of the Brazos and examined an "exposure" (known as the Brazos River Section-BRS) that Dr. Hildebrand had spent Saturday exhuming from recent muds that were deposited by the river. The BRS is one of the best exposed and most complete sections of K-T boundary in this area, including breccias and sandstones that were deposited from tsunamis produced from the Chicxulub event. Participants were also able to examine the "fireball" layer with elevated concentrations of the platinum group element Iridium (Ir). A lively discussion of the K-T boundary layer and its global distribution was a fitting end to this stop.

After lunch and a short drive, the group hiked to the final two stops of the trip along Darting Minnow and Cottonmouth Creeks. There participants examined additional, and less complete sections from the K-T event and attempted to avoid the local snake population.

Thanks to IFSG member Alan Hildebrand for leading the field trip and the 24 participants who helped us have a great day in the field. Here is a list of those who joined us:

Dallas Abbott	Lamont-Doherty Earth Obs.
Ann Bell	amateur scientist
Bill Deane	University of Tennessee
James Day	University of Tennessee
Clara Eberhardy	Brown University
Carolyn Ernst	Brown University
Scotty Forrester	Mann Middle School
Jennifer Glidewell	Geos. & Earth Marine Serv.
Scott Harris	Brown University
Eddy Hill	University of Tennessee
Anton Kearsley	Natural History Museum, London
Penny King	Western Ontario University
Keith Milam	University of Tennessee

Jan Knox	TX Geol. Survey (retired)
Orion Knox	architect (retired)
Molly McCanta	Brown University
Gordon Osinski	Canadian Space Agency
Veronica Peet	University of Pittsburgh
Jen Piatek	University of Tennessee
David Rajmon	Shell Corporation
Mark Thompson	Kentucky Geol. Survey
Brad Thomson	Brown University
Livio Tornabene	University of Tennessee
Jon Eckberg	University of Houston

2005 IFSG Annual Meeting

The Impact Field Studies Group held its 2nd Annual Meeting on Thursday, March 17, 2005 in the Amphitheatre Room of the South Shore Harbour and Resort Center in Clear Lake, Texas. The meeting was in conjunction with the 36th Annual Lunar and Planetary Science Conference. Approximately 50 IFSG members and guests met and heard a presentation by our invited speaker, Shawn Wright of Arizona State University. Shawn is an IFSG member and PhD candidate from Arizona State University. Shawn shared his research and field experiences at the Lonar Crater, India. His presentation also focused on the utility of remote sensing data in doing field-based research at impact sites.

The featured presentation was followed by the Year-in-Review by IFSG member Keith Milam. Keith discussed the past year's field trips to the Marquez Dome and Serpent Mound impact structures, in addition to this year's trip to the K-T boundary layer. Keith and IFSG webmaster, Bill Deane, highlighted upcoming initiatives, such as the re-design of our publication *Impacts in the Field* and exciting new interactive additions to the IFSG website. Thanks to all of those who attended and welcome to the new members who joined us following the meeting.

New Members

Over the past year, the IFSG has doubled in membership to 45 active members. The IFSG would like to welcome the newest members to our ranks:

Melissa R. Cox, from Southwest Missouri State University in Springfield, Missouri, has joined the IFSG. Melissa is a graduate student working with Kevin Evans to re-map the suspected Weableu-Osceola impact structure. In addition to the Weableu-Osceola, she has also spent time in the field at the nearby Crooked Creek (U.S.) structure.

George Davis joins us from the Geotechnical Section of the Missouri Department of Transportation. George has an avid interest in Missouri impact sites and studies the effects of impact terrain on highway construction. Joes has been in the field at the Decaturville and Weaubleau-Osceola, Missouri impact structures.

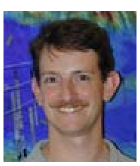
James Day is a Postdoctoral Fellow and Research Associate at the Planetary Geosciences Institute at the University of Tennessee. James utilizes radiogenic isotopes, especially the Re-Os system, to investigate the origin and evolution of planetary mantles (Earth, Moon, Mars). He is also actively involved in lunar meteorite geochemistry and is interested using radiogenic isotopes to date terrestrial impact events.

Joe Fandrich hails from Mesa State College, Grand Junction, Colorado. Joe's research deals with bolide impacts into wet targets and the remaining trace evidence. He has visited several U.S. sites including Barringer, AZ, Sierra Madera, TX and Upheaval Dome, UT impact sites in addition to the Odessa, TX crater field.

Marc Fries joins us from the Carnegie Institution in Washington, D. C. Marc is actively doing astrobiology-related research.

Jennifer Glidewell is a geophysicist currently employed by the Geoscience Earth and Marine Service in Houston, Texas. Jennifer has experience at several terrestrial impacts and does extensive community outreach at Space Center Houston, next to the Johnson Spaceflight Center.

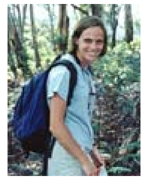
Tamara Goldin joins us from the University of Arizona, where she does Chicxulub research, impact modeling, and is interested in the structural geology of craters. Tamara has visited several impact sites in the U.S. including Barringer Meteor Crater and Wetumpka, AL.



Albert Haldemann joins the IFSG from the NASA-Jet Propulsion Laboratory in Pasadena, CA. Albert is an active member of the Mars Exploration Rover team and has visited the Barringer and Sudbury impact sites. Albert's research involves martian crater degradation and radar observations.

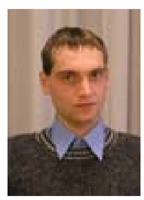
Essam Heggy is one of our latest members from the Lunar and Planetary Institute, Houston, TX. Essam research interests include planetary geophysics, ground penetrating radar, and synthetic aperature radar. Essam recently discovered a field of small impact craters in the southwest Egyptian desert.

J. Wright Horton, Jr. joins us from the United States Geological Survey in Reston, Virginia. Horton is actively involved in the ongoing research at the Chesapeake Bay impact structure in the eastern United States. His other research interests include marine impact structures, impactites, and the structural geology of impacts. He has been around the world at several impact sites including the Ries (Germany), Lockne (Sweden), and Barringer-Meteor Crater (USA) structures.



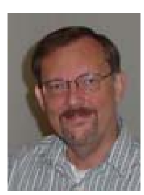
Penny King joins us from Western Ontario University, Canada. Penny is a new faculty member involved in creating a planetary program at Western Ontario University. Penny's interests are wide-ranging, from remote sensing to experimental petrology. Penny has visited several impact sites around the world and is actively involved in research at the Flynn Creek, TN impact structure.

Gunter Kletetschka joins us from the NASA Goddard Spaceflight Center, Maryland. Gunther's research involves impact magnetism. He has visited several impact sites including, Chicxulub, Manicoaguan, Canada, and Barringer Meteor Crater.



Tomas Kohout is one of our new international members from the University of Helsinki. His research deals with the physical properties of meteorites and asteroids. Tomas has been in the field at the Morasko, Poland and Keurusselka, Finland impact structures.

Goro Komatsu is another one of our new international members from the International Research School of Planetary Sciences, Universita d' Annunzio, Pescara, Italy. Goro does research on terrestrial and martian impact cratering.



Kenneth Kuehn joins us from Western Kentucky University. Ken is a sedimentary geologist who specializes in coal petrology. He is primarily interested in confirmed/suspected impact sites in Kentucky and has done field work at the Middlesboro, KY impact crater.

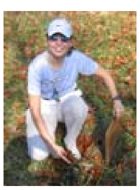
Rhiannon Mayne is a PhD candidate from the Planetary Geosciences Institute at the University of Tennessee. She is actively doing geochemical and spectral research on eucrites in preparation for the upcoming Dawn mission to asteroid Vesta and Ceres.

Jared R. Morrow hails from the University of Northern Colorado. Jared has been involved in research related to the Alamo (Nevada, USA) impact event and impact-related mass extinctions. He has visited several impact sites the world-over including the Vredefort (South Africa), Popigai (Russia)), Ries (Germany), and Steinheim (Germany) impact structures and several craters and impact-related sites in the U.S. including Wetumpka, Chesapeake Bay, Upheaval Dome, Barringer-Meteor Crater, Weaubleau-Osceola, Decaturville, the Alamo breccia, and the Raton basin.

Veronica Peet joins us from the University of Pittsburgh. Veronica is working to develop morphologic criteria for distinguishing between impact and volcanic craters using remote sensing

Jennifer Piatek is a Postdoctoral Research Fellow at the Planetary Geosciences Institute, University of Tennessee. Jen specializes in thermal infrared spectroscopy of the martian surface using data from the TES and THEMIS instruments.

Jeffrey Plescia joins us from the Applied Physics Lab at John Hopkins University, Maryland. He primary research interest includes gravity studies of impact craters to understand their structure.



Karen Stockstill is finishing her PhD at the University of Tennessee and will soon be assuming a position as a Postdoctoral Fellow at the University of Hawai'i. Karen's research has focused on melt inclusions in martian meterorites and the search for carbonates in martian craters suspected to have once served as paleolake basins.

Upcoming Events

2005 Middlesboro - Flynn Creek METSOC Field Trip

Mark your calendars! A new field trip opportunity is available in conjunction with the 2005 Annual Meteoritical Society Meeting in Gatlinburg, TN (Sept. 12-16, 2005). This post-meeting field trip is planned for Sept. 16-18, 2005 (Friday through Sunday). The trip is limited to 30 people. Participants will first visit the Middlesboro impact structure in southeastern Kentucky and then the Flynn Creek impact structure in central Tennessee. For more information, visit the 2005 METSOC Gatlinburg website at: http://geoweb.gg. utk.edu/2005/metsoc2005.html.

Coming in the future issues of *Impacts in the Field. . .*

- **Inside the Central Uplift – IFSG Field Reports from Hawkins Impact Cave**
- **"In the Field" at Lonar Crater, India**
- **More Upcoming Events**
- **More New Members**

Where in the World? **Can you identify this terrestrial impact crater? To find the answer, go on-line to the IFSG website at http://web.eps.utk.edu/ifsg.htm and click on the 'Earth' link under Panorama menu bar.**