

GR Letter

Using magnetic susceptibility to find Precambrian impact ejecta: A proposal

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Abstract

Layers with high magnetic susceptibility contain heavy minerals that are the most likely to preserve signatures of impact in metamorphosed Precambrian rocks. The following impact indicators are resistant to alteration and metamorphism and are likely to be found in heavy mineral layers: impact diamond, SiC, shocked zircon, high-pressure TiO₂ phases, reidite, and high-pressure chromite. Coesite and stishovite could also be present but are not likely to be preserved in rocks metamorphosed above the greenschist facies. Looking for layers with high magnetic susceptibility will also identify layers that might contain concentrations of zircon for dating.

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1. Introduction

Given the known impact rate for Precambrian time, there were at least 300 large impacts (crater diameter > 80 km) onto the Earth (Abbott and Hagstrum, 2004). However, very few Precambrian impact ejecta layers have been found. So far, less than ten Archean impact ejecta layers are known (Byerly and Lowe, 1994; Hassler and Simonson, 1997; Simonson et al., 1999, 2000). Each of these layers has impact spherules that are large enough to be observed with the naked eye. However, most of the large Precambrian impacts did not produce spherules of this size. At least 70% of the large impacts were into Precambrian ocean basins. At typical abyssal depths (e.g. 3800 m), impactors must have diameters about three times larger to produce the same size of impact crater and corresponding impact spherule as on land. Impact spherules are very low density and are highly vulnerable to metamorphic alteration. As a result, only the largest impact spherules can be confidently identified in Precambrian successions. Thus, some other method must be devised to locate and date impact ejecta layers in Precambrian sediments.

Most Precambrian sediments that are considered low grade are greenschist facies, and have been heated to temperatures of 150 to 300 °C. Under greenschist facies, metamorphism, impact glass, feldspar, olivine, and pyroxene generally are completely altered. Shocked quartz may be preserved but it is too common a mineral for the shocked grains to be readily found in most sedimentary successions. The minerals that are least vulnerable to alteration within sediments with a detrital source are those that constitute the heavy mineral fraction. Because heavy mineral-rich layers have a higher magnetic susceptibility than surrounding layers due to their magnetite and ilmenite content, detailed measurements of magnetic susceptibility can find layers that are enriched in heavy minerals. As zircon can be used for dating, this is a useful chronostratigraphic approach even if no impact indicators are found. The sediments that are most amenable to this type of work are shales, carbonates and poorly lithified siltstones.

2. Magnetic susceptibility as a marker for impact ejecta layers

Impacts produce ejecta that are composed of three components: broken rock fragments from the basement, impact glass, and condensed minerals and metal from the impact vapor plume. The broken rock fragments are the most abundant

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component of the proximal ejecta and are quite abundant in the more distal ejecta (Schulte and Kontny, 2005). In an oceanic impact, the near surface sediments are usually shales, carbonates, and/or siltstones. Unless the sediments have a high concentration of detrital iron, the sediments have a lower average magnetic susceptibility than the basaltic basement. Thus, proximal ejecta from an oceanic impact that are deposited within a typical oceanic sedimentary succession tend to have a higher magnetic susceptibility due to the higher inherent susceptibility of basalt fragments and basaltic glass compared to low Fe shales, carbonates and siltstones.

If an impact hits continental basement with more silicic igneous rocks, proximal impact ejecta containing an abundance of impact glass often have a high magnetic susceptibility due to crystals of mafic minerals with a high concentration of single domains (Kent et al., 2003). However, as the glass is altered, the higher susceptibility of the proximal impact ejecta will decay. Thus, proximal impact ejecta from continental impacts older than a few million years are unlikely to have a high magnetic susceptibility compared to the surrounding rocks. An example of this is the proximal ejecta layer from the 65 Ma Chixculub impact, which does not have a significantly higher magnetic susceptibility than the surrounding rocks (Schulte et al., 2005).

Distal impact ejecta contain a higher proportion of material from the impact vapor plume. Fe-rich spinel crystals are one of the best-known condensates from the impact vapor plume. The spinel crystals are usually quite small, which increases the proportion of single domain grains. Numerous Fe-rich minerals with a high magnetic susceptibility have been found in impact ejecta layers. We know of magnesioferrite spinels, magnetite, goethite, hematite, greigite and ilmenite (Worm and Banerjee, 1987; Verma et al., 2001; Wdowiak et al., 2001; Kent et al., 2003; Preisinger et al., 2002; Schulte et al., 2005). As a result, distal impact ejecta from both continental and oceanic impacts are likely to have a higher magnetic susceptibility than surrounding low Fe sedimentary rocks.

Although distal impact ejecta are likely to have a higher magnetic susceptibility than surrounding sediments, there are some important exceptions. In particular, volcanic ash layers also have a high magnetic susceptibility. However, as these layers are also useful for geochronology, this is not a drawback for geochronologists. In some cases, diagenesis along redox fronts may produce local highs in magnetic susceptibility (Schmitz et al., 2006). In coarse-grained sediments (median grain size is fine sand size or larger), ice-rafted glacial material, aeolian sediments, and unconformities may all appear as high

susceptibility layers. In general, successions of fine-grained carbonates, shales, and siltstones have the most uniform and lowest magnetic susceptibility. Marine shales often have low deposition rates of 1 m/million years and thus cover the most time for a given thickness of section. (At our postulated average rate of 300 impacts with near globally distributed ejecta layers over the 2400 million years of Precambrian time, a 16-m-thick shale sequence has a good possibility of yielding at least one layer from a global impact and additional layers from more local impacts.) Thus, if shales are available, these are the sediment type that is most likely to yield good results from detailed measurements of magnetic susceptibility.

3. Optimum techniques for susceptibility measurements

Magnetic susceptibility measurements are made in several ways. We know of three different techniques: loop susceptibility, susceptibility probe, and box measurements. The most common technique is the loop susceptibility measurement. This technique has the advantage that it can be automated. This is particularly useful for drill cores or other fairly uniform samples. However, loop susceptibility measurements average over about 11 cm of core, and thus have lower resolution than probe measurements. In addition, loop susceptibility measurements produce poor results near the ends of core sections and can result in 20-cm-wide gaps in measurement. A handheld susceptibility probe is the only device that is useful for outcrops in the field. The magnetic susceptibility probe averages over about a 2-cm interval and must be moved down the outcrop at 2-cm intervals. The degree of contact of the probe with the outcrop determines the magnitude of the susceptibility measurement, thus outcrop surfaces should be as smooth as possible. If drill core is available, it is more accurate to make probe measurements on the smooth top of the drill core. However, susceptibility measurements on outcrops are preferable to none at all. Box susceptibility measurements are useful for comparing samples acquired in the field. The samples should first be coarsely crushed and then put into the standard 1-cm square boxes that are used for laboratory measurements of magnetic susceptibility. The box measurements are the most accurate and can be used to determine which samples are the best prospects for more detailed work.

The most important principle to remember in any stratigraphic succession is that the absolute value of susceptibility is not as important as the susceptibility contrast with surrounding sediments. For example, calcium carbonate has a negative

Table 1
Heavy minerals useful as impact indicators

Mineral/Phase	Density	High-pressure polymorph	Usefulness as impact indicator
SiC (Moissanite)	3.21	No, but 6H and 15R are very high T polytypes	Some polymorphs unique to impacts, very resistant to acids
Diamond	3.51	Lonsdaleite	Hexagonal diamond lonsdaleite unique to impacts, very resistant to acids
Rutile (TiO ₂)	4.26	Yes, two	High-pressure phases found in impact ejecta
Zircon (ZrSiO ₄)	4.65	Reidite (30 to 53 GPa)	Forms pdfs during shock metamorphism, has a high-pressure polymorph
Chromite FeCr ₂ O ₄	5.09	Yes (20–23 GPa and 1800–2000 °C)	High-pressure phase so far found only in meteorites
Stishovite	4.28	Is one	High-pressure polymorph of quartz – unique to impacts
Coesite	2.93	Is one	High-pressure polymorph of quartz – unique to impacts

magnetic susceptibility, thus the average magnetic susceptibility of all carbonate-rich sediments is quite low. Although the K/T boundary in limestones appears as a local susceptibility high in Oman (Ellwood et al., 2003), the absolute value of the susceptibility at the K/T boundary is quite low. Thus, continuous measurements (2-cm interval) of magnetic susceptibility over a moderate stratigraphic thickness are more valuable than discontinuous susceptibility measurements over a larger stratigraphic thickness.

4. Heavy minerals useful as impact indicators

Heavy minerals have a density of over 2.9 g/cm³. Heavy minerals that can be used as impact indicators are listed in Table 1 along with their densities. We include here all of the heavy minerals that are known impact indicators. Some of these heavy minerals are more resistant to metamorphism and are more likely to be useful in high-grade sequences. For example, some shocked zircons have been found in granulite facies rocks. In contrast, coesite and stishovite, the high-pressure phases of quartz, are unlikely to be preserved in rocks metamorphosed above the greenschist grade.

4.1. Translucent heavy minerals

SiC is usually translucent, has high relief, and has no cleavage. SiC is very resistant to metamorphism. In impact ejecta layers, SiC may be intergrown with impact diamond. The impact ejecta from the Ries crater may contain silicon carbide in association with impact diamond (Hough et al., 1995).

As manmade SiC has a disordered structure with a mixture of polytypes, it is unlikely to be mistaken for natural SiC. Silicon carbide with an ordered structure is commonly associated with meteorites and comets derived from interstellar space, or kimberlites and other alkaline rocks originating in the deep mantle (Lyakhovich, 1980; Nittler, 2003). Although silicon carbide with an ordered 6H structure has been found in nodules from the Canyon Diablo meteorite (Leung et al., 2004), typical extraterrestrial SiC has an ordered 2H or 3C type structure (Daulton et al., 2002). Because the 6H polytype of SiC forms at temperatures above 1700 °C under strongly reducing conditions, typical kimberlitic SiC has an ordered 6H type structure.

The 15R structure is unique to the high-pressure polymorph of SiC that forms within the diamond stability field (Lyakhovich, 1980; Varshavskiy and Shulyakov, 1967). Experimental studies to date cannot produce pure 15H. They have produced a mixture of 6H and 15R at temperatures above 2250 °C (Yoo and Matsunami, 1991), temperatures which would not occur at the surface of the Earth except during an impact. Therefore, SiC with a 6H structure found within a metamorphosed sedimentary sequence cannot have formed in situ but must have come either from diamond bearing rocks or impact ejecta. If the SiC has a 15R or mixed 6H/15R structure it must have come from an impact (Leung et al., 2004).

Zircon has high relief and conchoidal fracture. It is much more abundant than SiC and is relatively easy to find in assemblages of heavy minerals. If an impact ejecta layer contains shocked

zircons, the shocked zircons are sometimes a very high percentage of the overall zircon content. For example, shocked zircons make up 23% of the zircons recovered from the distal impact ejecta layer of the Chesapeake Bay crater (Glass et al., 2002).

Shocked zircon is readily identifiable from its shock lamellae. In addition, zircon has a high-pressure polymorph called reidite that forms at pressures between 30 and 53 GPa (Glass and Liu, 2001). In some cases, the shock lamellae in zircons are composed of reidite (Douglass et al., 1994). Above 90 GPa, zircon breaks down into ZrO₂ plus SiO₂.

Coesite and stishovite are the high-pressure polymorphs of quartz (Basu et al., 1988; French et al., 1972; Grieve and Pilkington, 1996). Both polymorphs are translucent in thin section but may be opaque in larger grains. Coesite appears bright white. If a sequence is deeply weathered, coesite may be the only heavy mineral with this appearance.

4.2. Opaque heavy minerals

Chromite is almost always opaque. It has a high-pressure polymorph that appears as bright lamellae in a backscattered image of a chromite grain imaged by a scanning electron microscope (Chen et al., 2003). The brighter appearance of the lamellae is due to the higher density of the chromite polymorph. These lamellae appear in chromite grains that are 5 to 40 µm in diameter. The lamellae are about 0.5 µm wide. The high-pressure phase of chromite is stable between 20 and 23 GPa and between 1800 and 2000 °C.

Rutile can be translucent to opaque. Rutile has two high-pressure polymorphs that are found in shocked gneisses of the Ries impact crater (El Goresy et al., 2001a; El Goresy et al., 2001b). The ultradense polymorph of rutile shows intense blue internal reflections under crossed polarizers in reflected light (El Goresy et al., 2001a). However, these high-pressure polymorphs are not stable above 500 °C. Thus, these two polymorphs are unlikely to be good impact indicators in rocks above the greenschist facies.

Impact diamond, or lonsdaleite is very different from the diamond found in kimberlite pipes (Masaitis et al., 1999; Shelkov et al., 1998). Lonsdaleite can be either clear or black and has a metallic luster in reflected light (Gurov et al., 1999; Vishnevsky and Raitala, 2000). Lonsdaleite is hexagonal and has characteristic convex crystal faces. Lonsdaleite is very hard and will scratch all other minerals. Diamond also is nearly insoluble and can be separated out by dissolving the rest of the rock-forming minerals. Generally, lonsdaleite crystals are only a few microns in diameter but impact diamonds over 100 µm in diameter have been found in the impact ejecta from the Popigai impact crater.

5. Laboratory technique

Although heavy mineral separation is most commonly used on unconsolidated sediments, it is quite practical for highly weathered shales and siltstones. These are precisely the type of sedimentary rock in which conventional impact indicators are very poorly preserved. We find that weathered clay-rich

sediments can be disaggregated with minimal crushing. The sediment grains are then separated into different size fractions with sieves. In order to get the most single grains, we recommend the 63 to 150 μm size fraction as a starting point. The grains are then separated by density using a centrifuge and sodium polytungstate. The latter material is quite safe to use and does not offer the prospect of liver damage and overall expense associated with heavy liquids. Because sodium polytungstate can be reused, it is relatively inexpensive to use for separation of heavy minerals.

6. Conclusions

Finding layers of high magnetic susceptibility in Precambrian sedimentary successions will also identify concentrations of heavy minerals. As many heavy minerals are resistant to erosion and metamorphism, heavy mineral layers associated with impacts are likely to preserve impact indicators. We have compiled a list of nine indicators of impact that could be found in heavy mineral-rich layers. As zircon is a heavy mineral that is useful for dating, this strategy may be particularly useful for geochronologists with an interest in impacts.

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