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The Beaverhead Impact Structure, SW Montana and Idaho: Implications for the Regional Geology of the Western U.S.

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The Beaverhead Impact Structure, SW Montana and Idaho: Implications for the Regional Geology of the Western U.S.

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Abstract

The Beaverhead impact structure in SW Montana and Idaho is an allochthonous fragment of a large impact structure (~ 100 km diameter) that was transported some distance eastward during the Cretaceous Sevier orogeny. It is the first tectonic fragment of a large impact structure identified in the geologic record. The present evidence for impact consists of shatter cones, pseudotachylites, and planar deformation features in quartz. The age of the impact is not well constrained but is estimated to be Neoproterozoic to Cambrian (1000-500 Ma).

The Beaverhead impact event must have created other features that may be preserved elsewhere in western Montana and Idaho. These include proximal and distal ejecta (which may be misinterpreted as diamictites and/or tuff horizons) and other fragments of the crater floor containing shatter cones and pseudotachylite. A large circular gravity, magnetic and topographic anomaly, which could be the root of the impact structure, has been identified near Challis, Idaho. An enigmatic lithic tuff, identified in drill cores from the Challis area and an intraformational quartzite breccia in the Leaton Gulch area may be impact-related deposits, but no definitive evidence of shock metamorphism has been observed in these materials.

The discovery of more pieces of the Beaverhead puzzle, as well as the recognition of other large impacts in the geologic record, are likely once the regional geologic community grows to accept the incidence of such events and becomes more familiar with the features of shock metamorphism in the field. To that end, the community of geologists in this area should integrate the Beaverhead structure into their research and teaching curriculum.

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Meteorite impact cratering is a fundamental geological process on solid-bodied planets (Shoemaker, 1977). While evidence of this is widely recognized on the other terrestrial planets in the solar system, the role of cratering in the geological evolution of the Earth is not widely appreciated. This is due, at least in part, to the fact that meteorite impacts, at this stage in Earth history, are rare events and, once formed, an impact crater can be obscured and eventually destroyed by the active tectonic and erosional processes that resurface the Earth. While roughly 20% of the 134+ impact structures identified worldwide are buried, and the rest are eroded to some level (Grieve, 1991), nearly all still retain some circular geometry. This not only reflects the bias in recognition toward young, fresh craters, but also reflects the fact that the identification of many of these features has relied on the remote sensing of circular topographic, gravity or magnetic anomalies (Dence and others, 1968).

However, large impacts (roughly 100 km in diameter and larger), while rare, may leave evidence that persists in the geologic record long after the destruction of the circular crater. Large impacts excavate deep into the crust and result in the uplift of lower crustal and mantle material (Grieve and others., 1981). Large impacts also produce a large volume of shock-deformed rocks and minerals, as well as crater ejecta material that may be transported great distances from the point of impact and preserved in sedimentary basins.

The Beaverhead impact structure in southwest Montana and Idaho is the first example of a tectonic fragment of a large impact structure preserved in an orogenic belt. As such, it provides important information about the preservation and identification of impact features in the geologic record which may lead to future discoveries. From the standpoint of regional geology, the Beaverhead impact structure may well provide a unique temporal and structural reference for the geological history of the western U.S. It is likely that more evidence of large impacts will be discovered once the regional geologic community is more attuned to the features of shock metamorphism in the field.

The Beaverhead structure is an allochthonous fragment of a large impact structure that was roughly 100 km in diameter (Hargraves and others, 1990, 1994) The fragment has been tectonically transported some distance eastward. The present evidence of impact is found entirely within the Cabin thrust plate, part of the Cretaceous Sevier fold and thrust system, and includes the presence of shatter cones, pseudotachylites, planar deformation features in quartz, and extensive brecciation. The age of the impact is not well constrained but is estimated to be Neoproterozoic (Plumb, 1991) to Cambrian, 1000 Ma - 500 Ma.

SHATTER CONES

Shatter cones are considered to be diagnostic indicators of meteorite impact and have been replicated in nuclear and high explosive cratering and laboratory impact experiments (Sharpton and Grieve, 1990). Shatter cones are conical fracture patterns developed during the passage of a shock wave through rock (Dietz, 1960). The surface of the cones has distinctive striations which radiate from small parasitic horsetail-like half cones on the face of larger cones (Figure 1). The diverging pattern of the striations is distinct from the parallel grooves formed on slickensides. After making appropriate corrections for post-impact deformation, shatter cones have been shown to point toward "ground zero" in several impact structures (e.g. Vredefort, South Africa; (Manton, 1965), Wells Creek, Tennessee; (Stearns and others, 1968), and Gosses Bluff, Australia; (Milton and others, 1972)).

At the Beaverhead structure, shatter cones occur over an area > 200 km^2 and are extremely well developed in the area north of Island Butte (Figure 2). They occur solely in sandstones and underlying granitic basement gneiss. There is a non-random pattern of shatter cone orientations that may be structurally significant. In the area north of Island Butte the shatter cones point steeply upward and generally northward. In the area of Erickson Creek the shatter cones point shallowly to the east and throughout basement gneisses the shatter cones point southward at a variety of angles.

In the area of Erickson Creek (Figure 2), the relationship between the shatter cones and sandstone bedding suggests that, at least in this area, much of the structural deformation found in the sandstones predates the impact. The attitude of sandstone bedding is variable, with many beds steeply dipping or overturned. However, the pointing direction of the shatter cones throughout this area is consistently shallow and to the east. This "negative fold test" using shatter cones suggests that deformation prior to the impact was substantial. However in the area of Island Butte the shatter cones have a more consistent relationship to bedding suggesting little deformation prior to impact.

The lack of any circular symmetry to the shatter cone orientations may suggest that they represent only a small segment of the original distribution of cones, and that much of the present deformation in the sandstones is older than the impact event. As shatter cones are formed only in the central third of large impact craters, it is the present truncated distribution of cones which suggests an original crater diameter of at least 75-100 km in diameter.

PSEUDOTACHYLITES

Pseudotachylites occur over an area of 50 km^2. These rocks have been found in three small localities in the sandstones, two at Island Butte, and one at Erickson Creek, but are much more numerous in the crystalline basement rocks to the east and are particularly well developed in the area of Law Canyon (Figure 1). Small pseudotachylite dikes are also found in a few locations in the southernmost exposure of basement gneisses near Deadman Creek.

Pseudotachylites are easily misidentified in the field as igneous rocks because of their dark aphanitic and fluidal texture and their intrusive relationship. Similarly, those present in sandstones may be confused with the products of soft-sediment deformation. They can also contain vesicles, but commonly lack any igneous texture or phenocrysts in thin section and often appear to be the product solely of cataclasis. Another distinctive feature of pseudotachylites is their clast population which is derived solely from the local wall rocks.

Pseudotachylites are found in both the impact and tectonic environment and criteria for distinguishing between these have yet to be established. Unlike tectonic pseudotachylites, which are formed along fault surfaces (Sibson, 1975) with specific tectonically controlled orientations and distributions, impact-pseudotachylite dikes show no preferred orientation of occurrence. Commonly, impact-generated pseudotachylites are thicker and more abundant than those formed by tectonic processes (e.g. Dressler, 1984). However, this distinction may be difficult to apply in the distal parts of impact structures where pseudotachylite veins and dikes are smaller.

There are several lines of evidence that suggest that the pseudotachylites in the Beaverhead area are related to the event that formed the shatter cones, and not to later deformation caused by Cretaceous shortening or Tertiary extension. First, the pseudotachylites are most abundant in the area with the highest concentration of shatter cones (though individual outcrops only contain one or the other). Furthermore, while brecciation related to Tertiary extension is common, the pseudotachylites (especially those with a fluidal texture and vesicles) are not found along the later thrust and normal faults in the area. Second, the pseudotachylites occur in pods as well as dikes and veins and there is a distinct lack of slip surfaces, and the paucity of slip surfaces associated with pseudotachylites from impact structures has been noted elsewhere(e.g. Rochechouart, France; Lambert, 1981)). Third, the pseudotachylite dikes in the Law Canyon area (up to 1 m in thickness) are thicker than those reported in the tectonic setting (e.g. Magloughlin, 1989). Finally, some quartz grains within the pseudotachylite contain planar deformation features which have crystallographic orientations that are consistent with an impact origin (Fiske and others, 1994).

Small breccia dikes and veinlets of pseudotachylite are found in the southernmost exposure of crystalline basement rocks, in the vicinity of Deadman Creek. Planar deformation features are also found within quartz grains from these pseudotachylite dikes and their crystallographic orientations are similar to those observed from shock-deformed rocks (Fiske and others., 1994). However, no shatter cones have been found in these rocks so far, and thus it is difficult to correlate these pseudotachylites with those in the north.

AGE CONSTRAINTS

Up to now, stratigraphic relations provide the best constraint on the age of the impact event. The youngest rocks which contain shatter cones are massive to medium-bedded feldspathic quartzites, tentatively correlated to the Middle Proterozoic Lemhi Group (Big Creek and Gunsight Fm; Ruppel, written communication, 1994) defined by Ruppel (1975). However, the presence of glauconite and other sedimentological features in some units suggest to Skipp and Link (1992) an association with the Late Proterozoic and Lower Cambrian Wilbert Formation. Quartz and quartz-hematite veins within the quartzites are cross-cut by the shatter cone surfaces, suggesting that these rocks were lithified prior to impact. Adjacent but fault-bounded units of Ordovician Summerhouse Formation and Mississippian to Permian clastic and carbonate rocks do not contain shatter cones.

$^{39}Ar/^{40}Ar$ analyses of the pseudotachylites from Law Canyon (see Fiske and others., 1994) are difficult to interpret. The fine-grained pseudotachylite matrix is highly contaminated with atmospheric argon. Feldspar clasts from one sample yielded Cretaceous ages whereas another similar sample yielded Permian ages. A sandstone-hosted pseudotachylite gave apparent

Precambrian ages but is particularly contaminated with atmospheric argon. If the pseudotachylite was originally Precambrian, the variable ages suggest varying degrees of thermal resetting.

Preliminary paleomagnetic results from 11 samples from one body of pseudotachylite have been obtained (K.S. Kellogg, written commun., 1993). The remanence was extremely stable during alternating-field demagnetization, demonstrating single-component behavior, and yielded consistent northerly declination, positive inclination, vectors consistent with a Tertiary field direction. As a westerly declination is expected for a late Precambrian magnetization, these results suggest either that the pseudotachylite is younger and unrelated to the impact event, that it was completely reset during the Tertiary, or that considerable tectonic rotation about vertical axes occurred during Cretaceous thrusting. Further combined paleomagnetic and $^{39}Ar/^{40}Ar$ studies of specific samples may be necessary in order to reconcile the results of these two techniques.

IMPLICATIONS FOR THE REGIONAL GEOLOGIC HISTORY

Missing ejecta deposits

Meteorite impacts of this scale spread extensive deposits of ejecta material over distances of several hundred kilometers. Proximal ejecta deposits (e.g. Bunte breccia, *Ries , Germany;* (Pohl and others., 1977)) as well as distal ejecta (e.g. *Acraman, Australia;* (Gostin and others, 1986)) have been identified from a few terrestrial impact craters. Distal ejecta deposits are typically thin and usually consist of poorly sorted angular sand-sized grains and rock fragments with occasional larger blocks. While these deposits resemble those formed by debris flow, or ice rafting, they can sometimes be identified as ejecta material by the rare occurrence of melt spherules, multiple sets of planar deformation features in quartz (Gostin and others, 1986; Alexopolous and others, 1988), the presence of trace quantities of coesite and stishovite (e.g.

McHone and others, 1989), and anomalously high concentrations of platinum group elements including iridium (e.g. Gostin and others, 1989). Indeed, the ejecta deposit associated with the Acraman impact structure in Australia was considered to be an air-fall tuff layer until the discovery of shocked quartz grains in 1986 (Gostin and others, 1986).

While no ejecta material from the Beaverhead impact has been found these materials may have been misidentified as endogenic deposits. Proximal deposits of thick impact breccias may bear some resemblances to tillites or diamictites (Oberbeck and others, 1993) and may also contain some features of shock metamorphism, though not nearly as much as the distal ejecta which, although volumetrically relatively minor, comes from the central portions of the crater and thus experiences higher pressures (Melosh, 1989).

Possible geophysical signature

Despite the tectonic dismemberment of the crater, the root of the Beaverhead impact structure may still be preserved as a geophysical anomaly. Studies of other impact craters suggest that the formation of a 100 km crater will result in 10 km of structural uplift of the basement (Grieve and others, 1981). Furthermore, the large-scale faulting associated with crater formation may provide zones of weakness later exploited by other tectonic processes. Large nearly coincident circular gravity and aeromagnetic anomalies (Figure 3) and a distinctive arcuate orientation of major faults, centered near Challis, Idaho, have been identified (Hargraves and others, 1994, McCafferty and others, 1993). The aeromagnetic feature consists of a series of magnetic highs most likely due to Eocene stocks associated with the Challis volcanics while the long wavelength gravity anomaly (roughly 100 km wavelength) suggests a deep seated mass of dense rocks (lower crust and upper mantle roots of the central uplift?) below the Teriary intrusives (McCafferty, written communication, 1994). While these features are not entirely coincident, their size is consistent with the estimations of the original size of the Beaverhead impact structure, and their position is compatible with estimations of thrust displacement in the region (Hargraves and others, 1994). But while the coincidence of these features is unusual by itself, it's relationship to the Beaverhead impact structure remains speculative.

Suspect deposits in the Challis area

With an extensive and diverse Precambrian and Paleozoic stratigraphy, complicated by intense Cretaceous tectonism and Tertiary extension, the geology of the Challis area is known to be unusually complicated (Hobbs and others, 1990, 1991). Literature searches followed by reconnaissance field investigations have yielded two intriguing features which might be related to the impact event.

Jacob (1990) reports an unexpected "silicic lithic tuff" encountered in a borehole beneath the lower Paleozoic sequence in the Bayhorse anticline. The hole, 3749 feet deep, was drilled approximately five miles west of Challis, Idaho (Figure 3). This unit was originally interpreted as a diamictite, but petrographic study by B. F. Leonard (written communication to S. W. Hobbs, 196?) "disclosed the volcanic nature of the matrix components." Despite these encouraging hints, study of the same samples and thin sections (kindly made available by S. W. Hobbs) has revealed no compelling evidence of shock deformation or melting.

An intraformational breccia zone, up to 20m thick, present in the Leaton Gulch area (late Precambrian?) (McIntyre and Hobbs, 1987) is another intriguing occurrence (Figure 3). This monolithologic breccia, consisting of angular to subrounded quartzite fragments up to 10 meters in size, suspended in a silicified sand matrix, is well exposed in and around the road up Leaton Gulch in the Pahsimeroi mountains east of Challis. Underlying units are intact. Reconnaissance field examination has confirmed that this breccia is intraformational, but it is not yet certain that there is only one layer. Thin section examination has revealed considerable evidence of strain including undulatory extinction and planar fractures in quartz, but again, nothing diagnostic of shock deformation. Whatever the origin of this breccia, the occurrence of quartzite breccia intraformational in quartzite is distinctly anomalous and merits further study.

CONCLUSIONS

Large meteorite impacts have occurred many times in Earth history. They produce features that may survive in the geologic record for long periods of time but are not easily recognized and thus often overlooked or misidentified. In addition, impact-induced earthquakes and tsunamis may substantially rework contemporaneous sedimentary units. Furthermore, in some cases, large impact structures may substantially alter existing sedimentation patterns due to subsidence and uplift, and may influence the tectonic development of the region by creating large scale crustal anomalies which may persist to great depths (e.g., Dressler and others, 1984). The offset in the Penokean orogenic front at the site of the Sudbury impact structure may reflect the interaction of orogeny-scale tectonic strain with a crustal-scale heterogeneity. The coincidence of the Beaverhead impact structure with the apex of the "south western Montana recess" in the Sevier front (Perry and others, 1987) is tantalizingly similar.

The Beaverhead impact structure is the largest in the U.S. and is the first allochthonous crater fragment identified in the geologic record. It poses challenging new problems for the regional geological community. Features such as an ejecta deposit, proximal breccias, and impact induced features such as earthquake and tsunami deposits, as well as more of the impact crater itself, may still be preserved elsewhere in the western U.S.

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Figure Captions

Figure 1. A shatter cone formed in sandstone from the northern end of Island Butte. Note the pronounced diverging striations on the surface. The area north of Island Butte is readily accessible by car and contains some of the finest shatter cones in the world.

Figure 2. Simplified geologic map of the Cabin Thrust Plate (modified from Skipp, 1988) showing the extent of shock deformation due to impact. Pseudotachylites are found in two localities in the sandstones (Island Butte and Erickson Creek) and are much more abundant in the granitic gneisses of Law Canyon and south. Small pseudotachylite dikes are also found in the area of Deadman Creek, at the southern end of Nicholia Basin, beyond the known extent of shatter cones.

Figure 3. Simplified map of eastern Idaho and western Montana showing the relationship between the allochthonous fragment of the Beaverhead impact structure marked as 1, the silicic lithic tuff described by Jacob (1990) marked as 2, and the intraformational breccias of Leaton Gulch marked as 3. The location and approximate extent of the aeromagnetic and long-wave gravity anomalies identified by McCafferty and others (1993) are represented by the dotted annular pattern and the striped circular region.

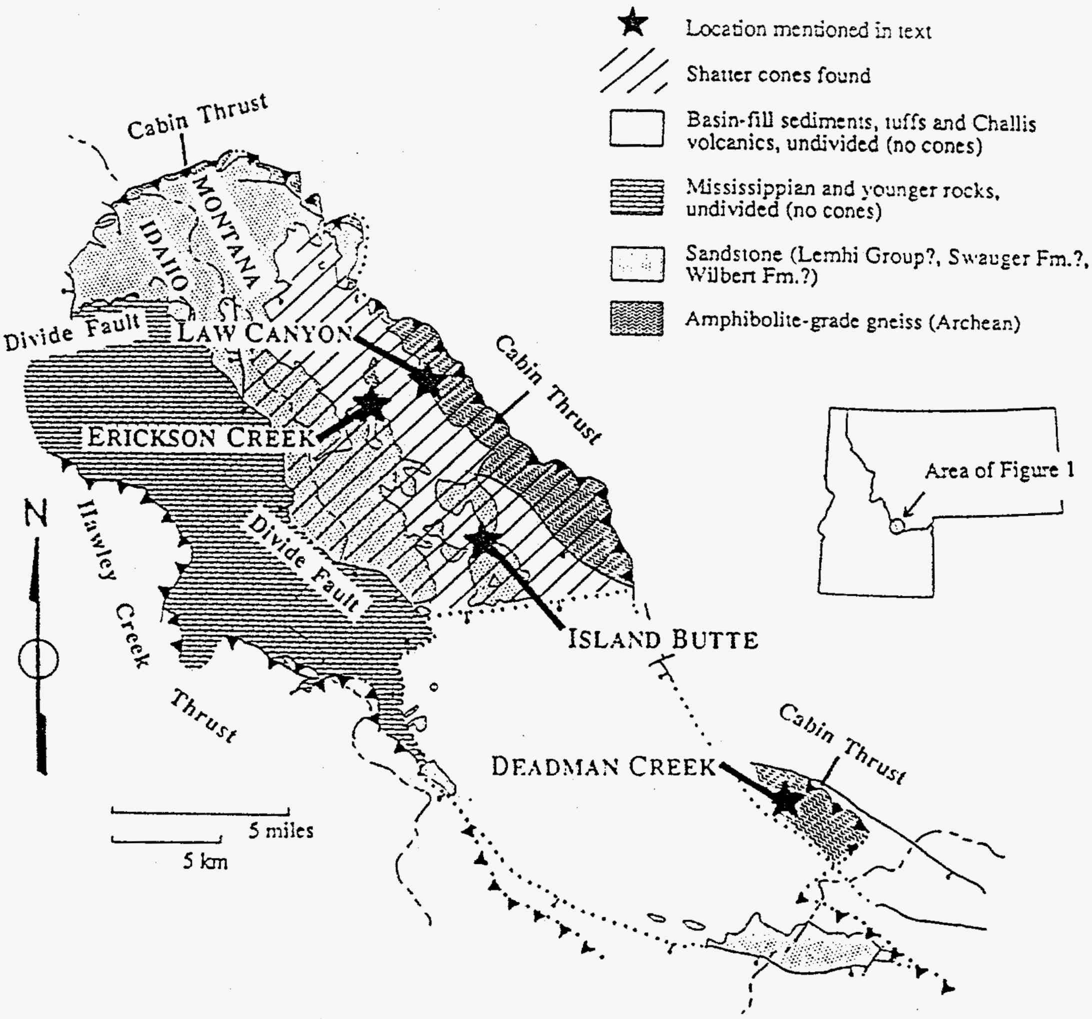

Figure 1

(Dick, you still have the original of this from the abstract, right?)

Figure 2 (Original photograph looks great)

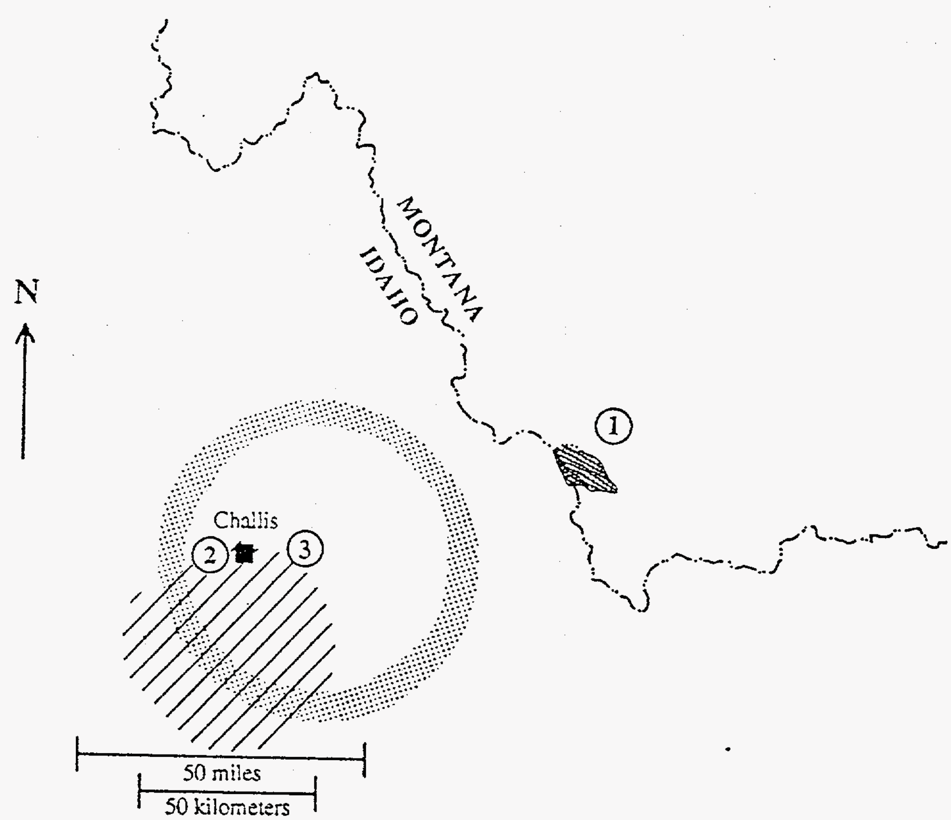

Figure 3