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The Peerless structure, Daniels County, northeastern Montana: A probable late Ordovician impact structure

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Abstract–The Peerless structure is an ~6 km-diameter sub-surface anomaly located in Daniels County, northeastern Montana. The disruption of sedimentary rock in the structure lies between 2624 to 2818 m below the topographic surface. Seismic mapping shows a typical complex crater composed of a central uplift ~2 km across, which shows structural uplift of up to 90 m, an annular ring ~4 km across, and an outer rim ~6 km in diameter. The youngest disrupted rock unit is the upper Ordovician Red River formation, which indicates that the structure was formed about 430–450 Ma ago.

INTRODUCTION

In the early 1980s, HS Resources, an independent oil and gas exploration and development company, conducted seismic surveys in northeastern Montana. These surveys revealed the presence of an anomalous circular structure in the subsurface northwest of Peerless, Montana (R. Frommer, personal communication).

In March 1995, HS Resources drilled the first of two wells, HSR-Hersel #14-5, into the structure. During drilling, two bits were replaced and an unusual rock sample from a depth of 2769 m was returned to the surface in a third. Drilling finally stopped at a depth of 3121 m with no oil or gas found.

Based on investigation of the unusual rock sample, which contained possible shock metamorphic features, the company was advised that potential oil recovery could come from the rim structure (M. Longman, personal communication). In September 1999, the Rustebakke 2-17H well was drilled into Ordovician target rocks on the outer edge of the south rim of the structure, approximately 2.4 km from the Hersel #14-5 well. Again, the well turned out to be dry and no further investigation is proposed for this site due to the lack of an oil or gas show.

GEOLOGICAL SETTING

The modern surface expression of the Williston basin consists primarily of flat, gently rolling plains approximately 500–1000 m above sea level. The basin covers an area of ~500,000 km^2 in North and South Dakota, eastern Montana, southern Saskatchewan, and southern Manitoba (Fig. 1). It is one of the largest structural basins on the North American continent and many of the structural features seen within the basin were initiated during the Precambrian and reactivated during several Phanerozoic orogenies (Sandberg 1964).

During the Paleozoic and early Mesozoic eras, the Williston basin is thought to have existed sequentially as: 1) an intracratonic basin; 2) a shelf area that bordered the eastern edge of a geosyncline located to the west; or 3) a region inundated by seas that flooded a trough area extending eastward into the central portion of the basin. This is evident in the unconformity bounded transgressive-regressive depositional cycles seen in the basin (Sloss 1963; Peterson and MacCary 1987).

Stratigraphy

The rock units of the Williston basin that are affected by the Peerless structure include Cambrian to Silurian sedimentary units (Deadwood, Winnipeg, Red River, Stony Mountain, Stonewall, and Interlake formations) as well as the top of the Precambrian crystalline rocks (Fig. 2).

The recognition and interpretation of stratigraphic layers affected by the Peerless structure are based primarily on their appearance in 3D seismic maps and 2D seismic profiles showing evidence of discontinuous or truncated seismic reflectors within the structure. The second piece of evidence supporting the interpretation of the affected layers comes from well log correlation across the structure into adjacent areas.

Precambrian Rocks

The Precambrian rocks of the Williston basin are primarily composed of metamorphosed igneous rocks, with

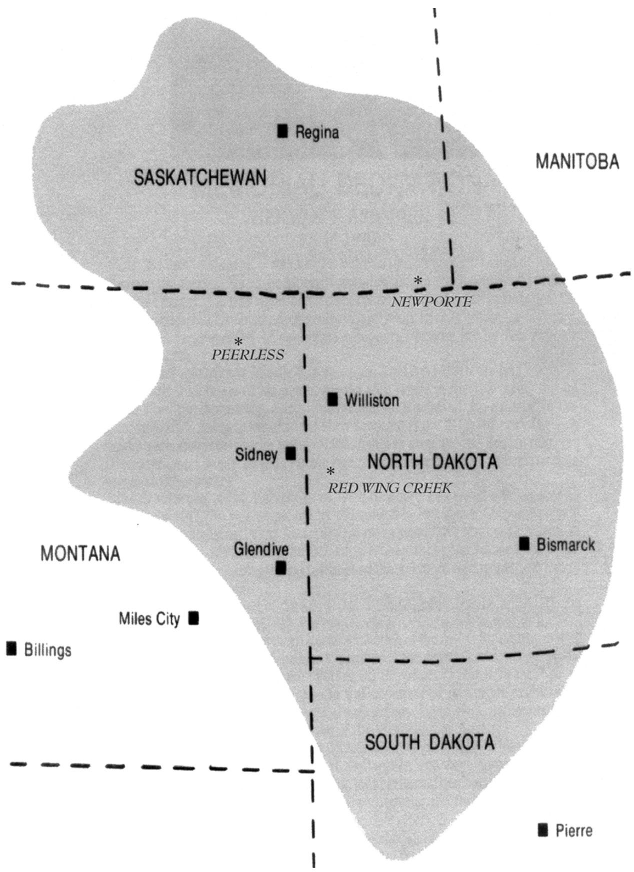

Fig. 1. Extent of the Williston basin on North American continent (modified from Estelle and Miller 1978). The approximate location of the Peerless structure, Newporte, and Red Wing Creek impact craters are indicated.

approximately 15 m of weathered granite wash or regolith on top of the crystalline bedrock. Based on well data from cores and cuttings, many of the rocks appear to be gneissic granite or related types of medium- to coarse-grained intrusive rocks with the remainder composed of amphibolite and other mafic to intermediate meta-igneous rocks.

Deadwood Formation

The Deadwood formation is considered to be mostly late Cambrian in age with only the upper portion classified as early Ordovician. It rests unconformably on eroded and locally weathered Precambrian metamorphic rocks and reaches 400 m thickness on the west side of the basin, thinning progressively eastward to a thin veneer. The average thickness of the Deadwood formation in the Williston basin region is approximately 140 m.

Although based on generally sparse well data, it appears that the Deadwood formation has two distinct lithologies. The basal bed is widespread and consists of grayish-red conglomeritic quartzitic sandstone, which ranges 10–60 m in thickness. The overlying upper unit is interbedded greenish-gray and gray shale, gray limestone, and limestone-pebble conglomerate. The upper unit is also characterized by an east-to-west facies change. On the west side of the basin, the upper unit contains relatively thick and abundant limestone beds, which become thinner and less common to the east.

Winnipeg Formation

The Winnipeg formation is middle Ordovician and is correlated throughout the Williston basin to outcrops at the type area in southwestern Manitoba. It overlies the Deadwood formation unconformably, except along the eastern margin of the basin, where this formation is absent. In those areas, the Winnipeg formation unconformably overlies the Precambrian metamorphic rocks.

In northwestern North Dakota, the Winnipeg formation attains a maximum thickness of about 110 m and thins westward and northward away form the central basin area. However, in the study area, the Winnipeg formation consists of three distinct units, which include a basal sandstone, a medial shale, and an upper dolomitic sandstone, that reach a maximum combined thickness of 73 m.

Red River Formation

The middle to upper Ordovician Red River formation conformably overlies the Winnipeg formation. However, in north-central Montana, where the Winnipeg formation is absent, it rests unconformably on the Deadwood formation. As with the Winnipeg formation, the Red River formation underlies the entire Williston basin, except where the monadnocks of South Dakota are located.

The Red River formation has a thickness of 125–215 m in the central basin area and thins to 90 m in Montana. In the central Williston basin, it consists primarily of gray to brownish-gray, slightly argillaceous, fossiliferous limestone which grades to largely unfossiliferous dolomite at the basin margins. The basal beds are usually sandy or silty in texture, with the upper beds being interbedded with anhydrite representing three complete evaporitic cycles (Sandberg 1961).

Stony Mountain Formation

The Stony Mountain formation of late Ordovician age conformably overlies the Red River formation. The Stony Mountain formation is far less widespread than the Red River formation in the Williston basin, and is often combined with the Red River formation in measured sections and well logs.

The Stony Mountain formation is 125–210 m thick in the central basin, thins to 30 m in eastern Montana, and is truncated by the Red River formation further to the west. It consists of distinct lower, middle, and upper units. The lower unit consists of gray to brownish-gray, highly argillaceous limestone grading to calcareous shale. The middle unit consists of yellowish-gray and brownish-gray dolomitic limestone with bedded anhydrite at the top. The upper unit is much thinner than the lower two units and consists of gray shaly and sandy limestone interbedded with calcareous shale.

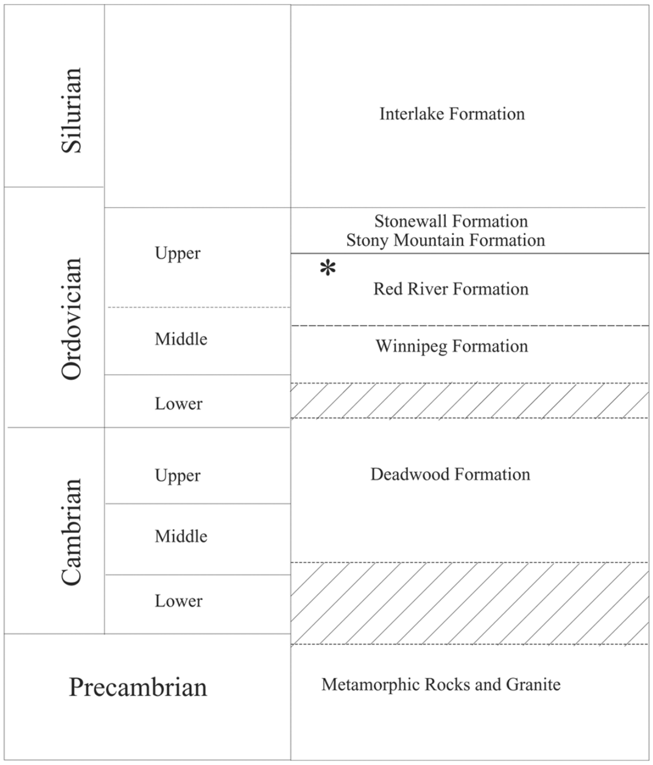

Fig. 2. Stratigraphic correlation chart of the Williston basin area (from Estelle and Miller 1978). The asterisk indicates the approximate stratigraphic level of the Peerless structure (the Stonewall formation was not distinguished from adjacent formations within the wells of this study).

Stonewall and Interlake Formations

Although the late Ordovician Stonewall and the Silurian Interlake differ in age, the two have similar lithologies.

The Stonewall formation is generally 15–30 m thick and predominately brownish-gray to light brownish-gray dolomite in the central basin area and yellowish-gray to white dolomite at the edges of the basin. The Interlake formation reaches the thickness of 90–330 m at the central basin and is composed primarily of interbedded brownish-gray, yellowish-gray, and light-gray to white dolomite and dolomite breccia, while at the basin margins, it is primarily light-gray to white dolomite. Small areas of erosion seen in east-central and north-central Montana were probably produced by channels cut into the Interlake formation during the early Devonian period (Sandberg 1961).

EVIDENCE FOR IMPACT ORIGIN

The HSR-Hersel #14-5 Well Cuttings and Well Logs

The investigation of the HSR-Hersel #14-5 well involved a review of the geologist's report, mud log, electric wireline well logs, and well cuttings. The lithology described in this section is based on the information presented in the geologist's report. All samples were investigated to confirm the overall lithology and stratigraphic units, but the primary focus was on a search for characteristics commonly found in impact craters.

Geologist's Report

Although the HSR-Hersel #14-5 well was only logged to a depth of 2906 m, the geologist continued describing the rock samples until drilling stopped at 3121 m. His summary presented several pieces of information with regard to the overall disruption of strata seen in the well: 1) the Red River formation appears to be less than normal in thickness and more sandy than usual for the area; 2) an 11 m-thick section of the Red River formation, from 2630 to 2641 m, is anomalously rich in organic content; 3) the 61 m-thick Winnipeg formation sandstone, present in several wells in the area, is believed to be entirely absent or only preserved as breccia blocks in the Hersel well; and 4) iridescent, coarse, rounded quartz grains, which occur throughout the disrupted area in the Red River, Winnipeg, and Deadwood formations, show microfracturing that is uncommon for quartz found in these formations in other parts of the basin (T. McCoy, personal communication).

Dipmeter Findings

A slight regional stratigraphic dip from the surface to a depth of 2620+ m is inferred from normal isopach formation thickness and the lack of any hole deviation. A dipmeter was run from 2500 to 2900 m with scattered chaotic dips (20–70°) recorded from 2650 to 2900 m and, when compared with well and lithologic logs for that interval, the disruption caused by the structure can be seen. Several short intervals between 2680 and 2900 m, which showed consistent dip angles and directions, are interpreted to be tilted, cohesive blocks within the Peerless uplift. No conventional cores were taken from this well but the geologist's report states that after three drilling cones were lost from a bit at a depth of 2769 m, the legs ("shanks") of the bit cored 13 cm of sandstone dipping at 80°.

Stratigraphy

In the Hersel well, the top of the Deadwood formation is at a depth of 2691 m and the unit extends down to Precambrian rocks at a depth of 3115 m, giving a formation thickness of approximately 424 m in this well. Although not an unusual thickness in this part of the basin, the depth of the formation top does pose some stratigraphic problems. Based on data obtained from the Rustebakke 2-17H well (located on the southern rim structure) and that of wells in the adjacent basin area, the top of the Deadwood formation in the Hersel well is uplifted from 30–90 m above average datum.

The overall lithology of the Deadwood formation appears consistent with other wells in the area. Quartz often occurs as medium to coarse, sub-rounded to rounded grains that are frosted and occasionally iridescent. Some loose grains have planar or conchoidal fractures across part of the grain, which results in grains missing one side or being sectioned into a round disc. These grains sometimes contain parallel microfractures. The loose grains often appear to have been plucked from the surrounding matrix, while those that remain cemented in the matrix appear to have been broken prior to cementation.

In the Hersel well, the Red River formation begins at a depth of 2625 m and continues down to the top of the Deadwood formation at a depth of 2691 m. The overall formation thickness cannot be determined as remnant breccia blocks thought to be from the Winnipeg formation are intermixed near the bottom of the interval. The lithology of the formation does not vary from what is seen in other areas of the basin, with two exceptions: the presence of interbedded medium to coarse, rounded quartz sand at the bottom of the interval and the occurrence of exceptionally organic-rich, near the top of the interval, dark brownish-grey to brownish-black, micromottled dolomite or kerogenite.

The Rustebakke 2-17H Well Cuttings and Well Logs

The Rustebakke 2-17H well did not penetrate as deep as the Hersel, only reaching the upper part of the Deadwood formation. The investigation of the Rustebakke 2-17H well involved a review of the mudlogger's report, the mud log, wireline well logs, and cuttings.

Mudlogger's Report

Again, the mudlogger's report contains several important general observations (K. Goldrick, personal communication). First, the organic layer seen in the Hersel well is also present in the Rustebakke well. However, the top of the layer is approximately 9 m lower in depth than in the Hersel well. As the Rustebakke well is located on the outside of the south rim, the layer was less obvious in the well logs and probably somewhat thinner due to its position.

Second, an anomalous sandstone layer (~6 m thick), which is present on the rim structure within this well, may be a wave-reworked ejecta layer or flap. This poorly-sorted sandstone is composed of unconsolidated, highly fractured quartz that is texturally and petrographically identical to the Winnipeg sandstone seen at lower depths in this well and within the sands of the Hersel well.

Stratigraphy

In the Rustebakke well, the top of the Deadwood formation is at a depth of 2789 m and only the upper 30 m of the formation were penetrated before drilling stopped. Based on this, the total formation thickness is unknown. However, unlike in the Hersel well, the top of the Deadwood formation in the Rustebakke well lies approximately at the expected normal depth for this formation, and it is not uplifted as seen in the Hersel well.

Also in contrast to the Hersel well, the Winnipeg formation is present in the Rustebakke well and has an appropriate thickness of 41 m for this area of the basin. It begins at a depth of 2747 m and continues down-hole to a gradational contact with the Deadwood formation at 2789 m. Its composition is exactly what would be anticipated for this area of the basin, with a quartz sandstone described as clear, white, poorly sorted, and unconsolidated, with abundant rounded glassy grains lacking apparent fractures.

The top of the Red River formation lies at a depth of 2674 m and continues down to the Winnipeg formation at 2747 m, comprising a thickness of 73 m. Again, both thickness and lithology are representative for this part of the basin. There are trace amounts of a black material on the face of several chips recovered in the Red River formation but no information is provided regarding the composition of that material in the mudlogger's report. Assumably, it is part of the same kerogenite layer seen in the Hersel well.

As in the Hersel well, the Stony Mountain formation has also been identified in the Rustebakke well. It begins at a depth of 2595 m and continues down to the top of the Red River formation at 2674 m, for a thickness of 79 m. An anomalous sandstone layer exists in the Stony Mountain formation noted to contain numerous loose quartz grains, some of which are broken in half or fractured and deformed.

PETROGRAPHY

In the HSR-Hersel #14-5 well, there were four intervals of primary interest for which thin-sections and photomicrographs were taken: 1) the kerogenite layer; 2) the location where three drill cones were lost and an unusual cored rock chip was returned to the surface; 3) where microfracturing of quartz was mentioned in the geologist's report and seen in well cutting samples; and 4) where intense brecciation is seen in the matrix and individual grains.

The shallowest depth at which samples were thin sectioned was between 2620–2650 m. This is the interval in which the organic-rich kerogenite beds were seen and many of the individual mineral grains have some black material associated with them. The samples revealed highly brecciated clastic and carbonate rocks with individual grains of quartz and glauconite that are internally fractured. Individual grains appear to have retained their exterior form and range in shape from rounded to angular. In a thin-section, the individual quartz grains also show undulatory extinction.

Several samples of breccia obtained between 2652–2664 m are comprised of many highly fractured grains forming the overall rock fabric. Individual quartz grains range from angular to rounded, with intense fracturing similar to that seen in the 2620–2650 m interval. Some grains have the appearance of surface striations in the form of parallel planes of multiple directions. Several of the quartz grains also have black material along parts of their surface, possibly the result of an organic-rich coating.

Thin-sections cut from the 2769 m level provided the best examples of planar fractures seen in the Peerless structure. Again, the sections from this interval have an overwhelming amount of brecciation, showing tightly packed internal fabric.

Individual quartz grains commonly have multiple sets of very obvious decorated planar fractures (Fig. 3). Grains at this depth also display undulatory extinction (Fig. 4), which is a petrographic characteristic of quartz within the overlying 610 m interval.

The interval of primary interest in the Rustebakke well, where thin sections and photomicrographs were taken, was a similarly anomalous sandstone that comprised approximately 6–9 m of the lower Stony Mountain formation. This sandstone layer is interbedded with carbonates. The cuttings from 2658–2664 m were sieved into 124–495 μm and >495 μm fractions, which were then thin-sectioned.

In both size fractions, the grains were found to be broken and fractured within the rock, which appears overall to have been stretched and banded during brecciation. The elongation occurred in both the matrix and in some of the grains associated with the matrix. Often, instead of a fine-grained matrix between coarser grains, breccia is found with highly fractured, angular smaller pieces in elongated strands with larger intact grains that are fractured internally.

Individual quartz grains were found scattered throughout the sections. Sometimes the grains had maintained their exterior form but showed disruption of their crystalline structure. Inclusion trails are seen in many of the quartz grains, as well as closely spaced parallel planes. These parallel planes, which are spaced 15–25 μm apart with an average at 20 μm, may represent poorly developed planar deformation features (PDFs). Another common feature seen in much of the quartz is undulatory extinction and polycrystalline micro-fabric, possibly due to crystallographic deformation and fracturing within the individual grains.

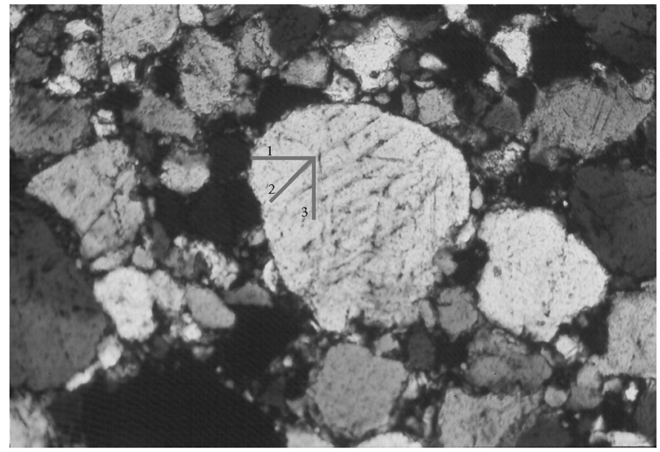

Fig. 3. Quartz with multiple sets of planar fractures (indicated) commonly seen at the 2769 m interval. Grains are imbedded within a highly fractured quartz matrix. The planar feature orientation #2 corresponds to probable basal Brazil twin (0001) direction. The field of view is 1.2 mm across, crossed polars.

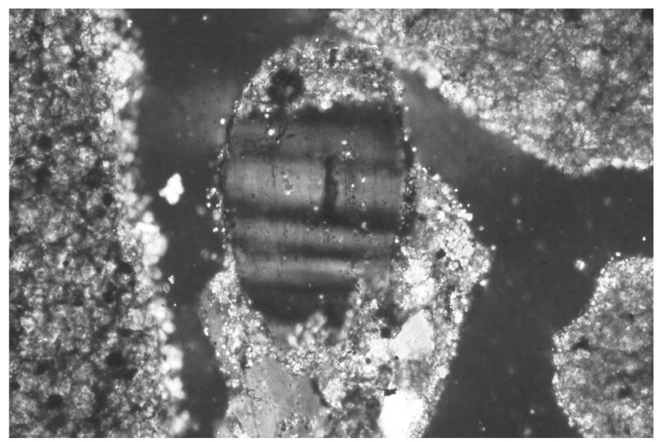

Fig. 4. Commonly occurring, fractured quartz with undulatory extinction 2769 m. The field of view is 1.2 mm across, crossed polars.

Seismic Mapping

The main body of the Peerless structure covers an area of ~31 km^2 within T35N, R44E, and R45E. HS Resources had several 3D seismic surveys conducted in the immediate area of the Peerless structure. This process provides images of contrasting lithologies in the subsurface by using the basic principle of the echo sounder. A high-energy sound signal is emitted from a surface device and then recorded after it reflects off the various lithologies. The time required for the sound to make the round trip is used to analyze the individual lithologies, traveling faster through some rocks than others.

Assumably, the structure continues in a close circular pattern, although seismic data were not received for the northern-most portion of the structure (Fig. 6). The structure can be subdivided into three clearly defined regions based on the travel time and interpreted structural relief of the given features: 1) a central uplift measuring ~1.6 km in diameter; 2) an annular ring measuring 4 km in diameter with variations seen on the west and south sides of the structure; and 3) an outer rim measuring ~6 km in diameter.

In addition to the 3D seismic map, two 2D seismic profiles were also constructed to evaluate parts of the structure. These profiles cut the structure from northwest to southeast through the HSR-Hersel #14-5 well (central uplift) and the Rustebakke 2-17H well (south rim) and from the west to the east through the central uplift. The profiles clearly illustrate the disruption of the stratigraphic layers across the structure.

The northwest-southeast profile provides a cross-section view of the structure (Fig. 6). The stratigraphic layers seen within the interior of the structure are not only disrupted but are also locally truncated. Those that remain are seen upwarping into the HSR-Hersel #14-5 well at the center of the structure. The Rustebakke 2-17H well is located at the east end of the picture just over the edge of the rim feature, where probable block faulting beneath the rim is present. The laterally continuous layers of the Stony Mountain and Interlake formations above the structure show some slight upwarping but no actual disruption, inferring that they were deposited after formation of the structure.

The west-east profile that begins just northeast of Ruby State 8-1, a well adjacent to the structure, offers a view through the central uplift (Fig. 7). The west rim shows disruption at its top, with additional overlying beds missing. The central uplift can be seen clearly in the center of the profile, marked by upwarped and truncated stratigraphic layers near the Hersel well. There is disruption in the upper beds of the central uplift, which are thought to be within the Red River and Winnipeg formation. The layers located beneath the structure appear coherent with strong, solid, continuous reflectors thought to be that of the bottom of the Deadwood formation and Precambrian rocks. The presence of an annular ring is not as pronounced as in Fig. 5. The eastern rim structure also shows the presence of block faulting. On this side, beds overlying the structure are downwarped above the rim, possibly due to localized relief on top of the structure or due to differential post-burial compaction.

Mode of Formation

Besides impact, four other probable formation processes have been suggested for structures similar to the Peerless structure: 1) volcanic intrusion; 2) salt diapirism; 3) erosion resulting in monadnocks; and 4) channel formation or karstification (French 1998).

The 3D seismic map and 2D seismic profiles provide evidence that stratigraphic disruption is restricted to Cambrian and Ordovician strata within the structure; beneath and

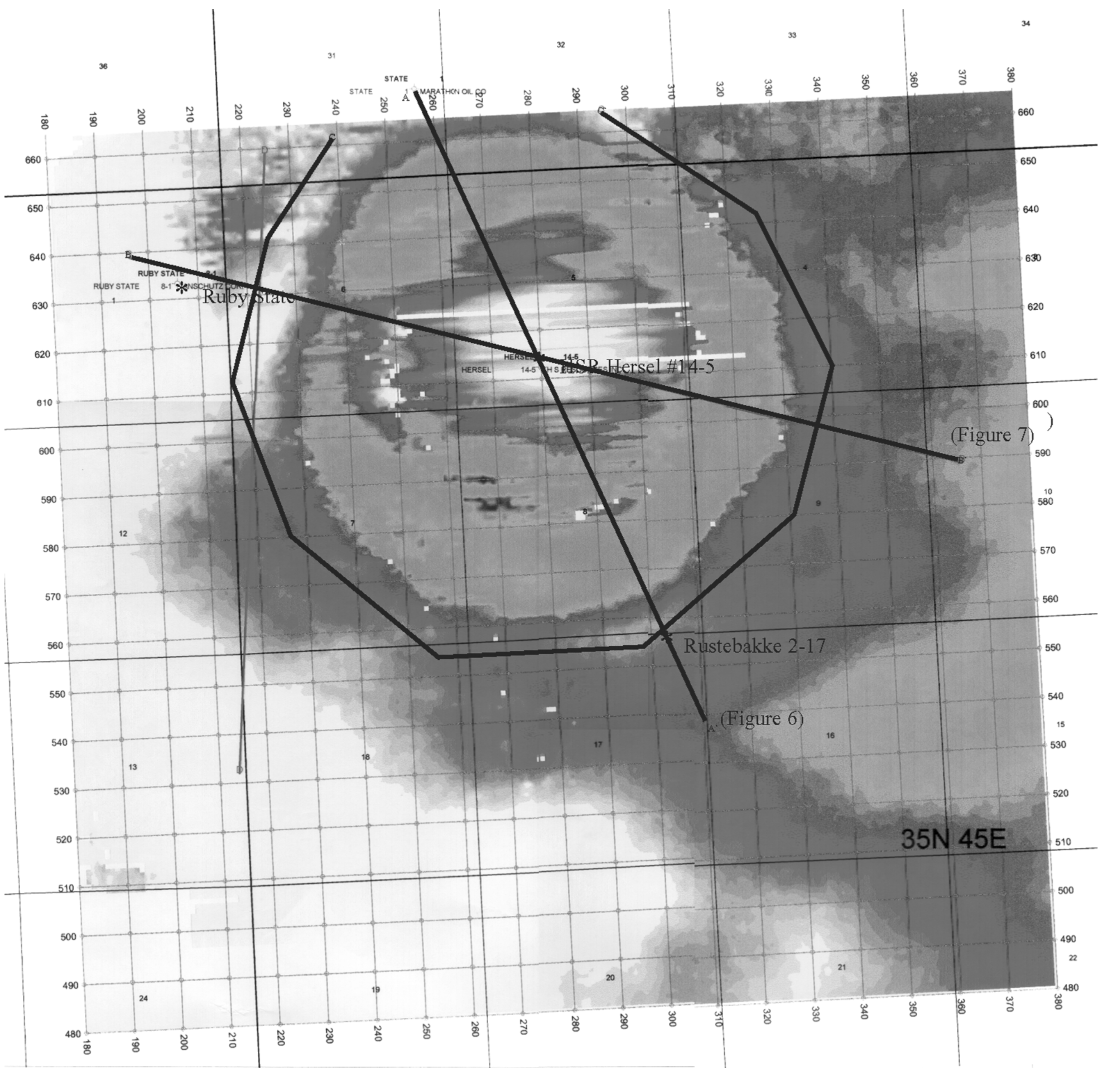

Fig. 5. 3D seismic map of the Peerless structure. Gray scale differences represent vertical travel time difference. Location of 2D seismic profiles (Figs. 6 and 7) are shown. The circular structure shown represents additional profiles requested but not used in this manuscript. The larger grid spacing is approximately 1.6 km. (Courtesy HS Resources)

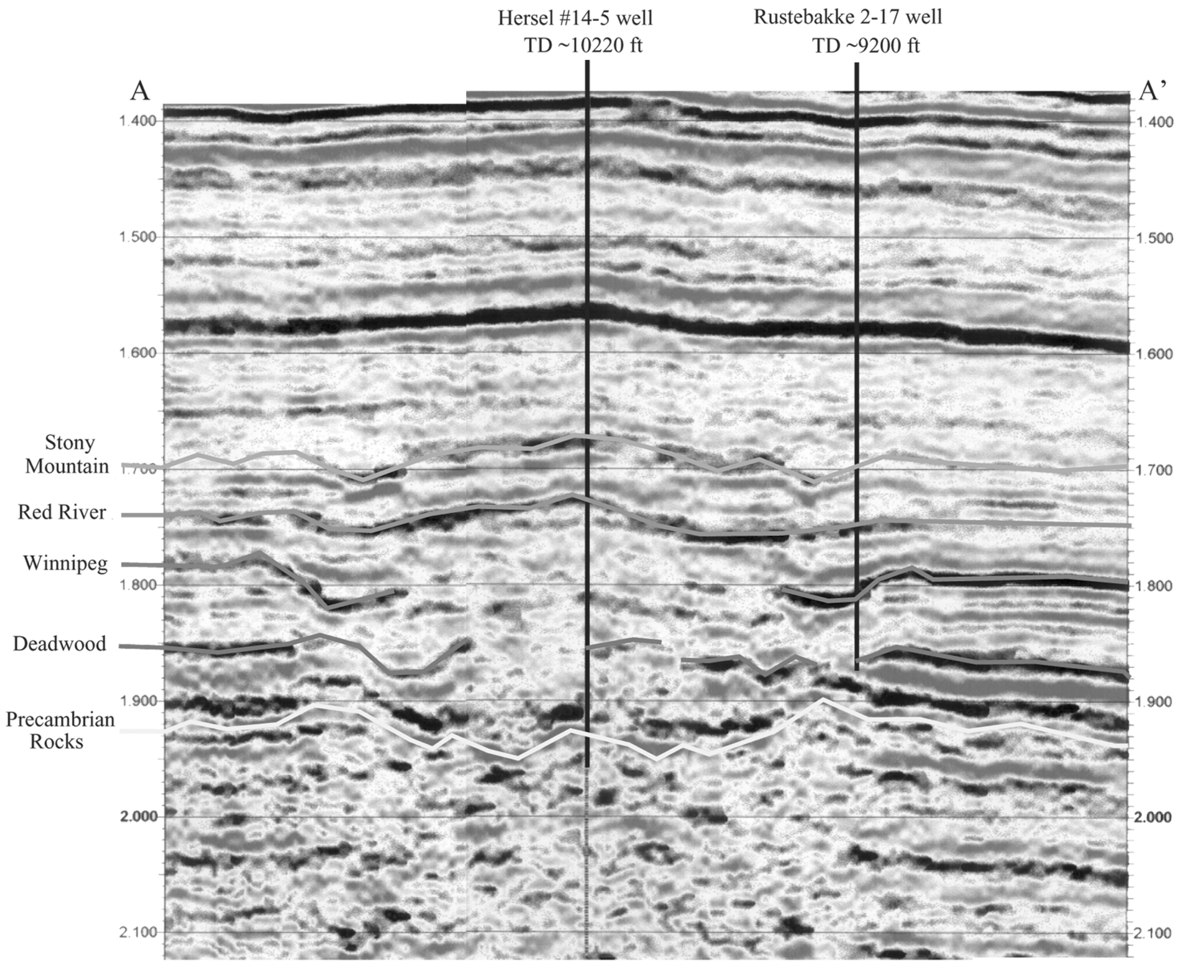

Fig. 6. 2D seismic profile northwest to southeast across Peerless structure (cross section line shown on Fig. 5). The vertical scale is two-way time traveled in seconds, velocity varies with lithology. Interpreted formation tops are shown. The location of the HSR-Hersel #14-5 and Rustebakke 2-17H wells are identified. (Courtesy HS Resources)

adjacent to the structure, the stratigraphic sequence is normal and undeformed. Also, the complete lack of any igneous rocks within the structure or adjacent areas suggests that volcanism was not the formation process for the Peerless structure.

Salt diapirism is the process by which plastic deformation of evaporite beds will cause an upwarping of the beds to form a dome-like structure. The Peerless structure is bounded below by the Cambrian Deadwood formation of sandstone and shale with no evaporite layers located below the structure. Also, the overall morphology of the Peerless structure does not represent a dome-like structure and, thus, precludes it being formed as a salt dome.

Subsurface monadnocks are present in both north-central Montana and southeastern South Dakota (Sandberg 1962). They form low plateaus of Precambrian rocks over which younger stratigraphic layers are draped. The Peerless structure is underlain by relatively undisturbed, flat-lying sedimentary strata, which separates it from a generally even Precambrian surface. Therefore, a monadnock origin for the Peerless structure is unlikely.

The presence of erosional channels found in Devonian rocks in the Williston basin (Sandberg 1961) has led to the question of whether or not their presence may have been a potential formation process for the Peerless structure. Erosional channels would produce linear structures in the topography. The overall relief of the Peerless structure, including the upward vertical displacement of some of the stratigraphic layers, does not resemble erosional channels. Furthermore, the erosional channel features occur in much younger rocks than that of the Peerless structure as groups of linear trench-like features and not as an isolated single body, arguing against this type of formation.

Karstification of soluble carbonate rocks usually produces a collapse due to dissolution of the rocks into groups of small circular collapse features. However, the overall relief of the Peerless structure with vertical displacement of some of the stratigraphic layers argues against such formation of the structure.

Dence (1972), French (1998), and others have described a set of criteria by which impact structures may be

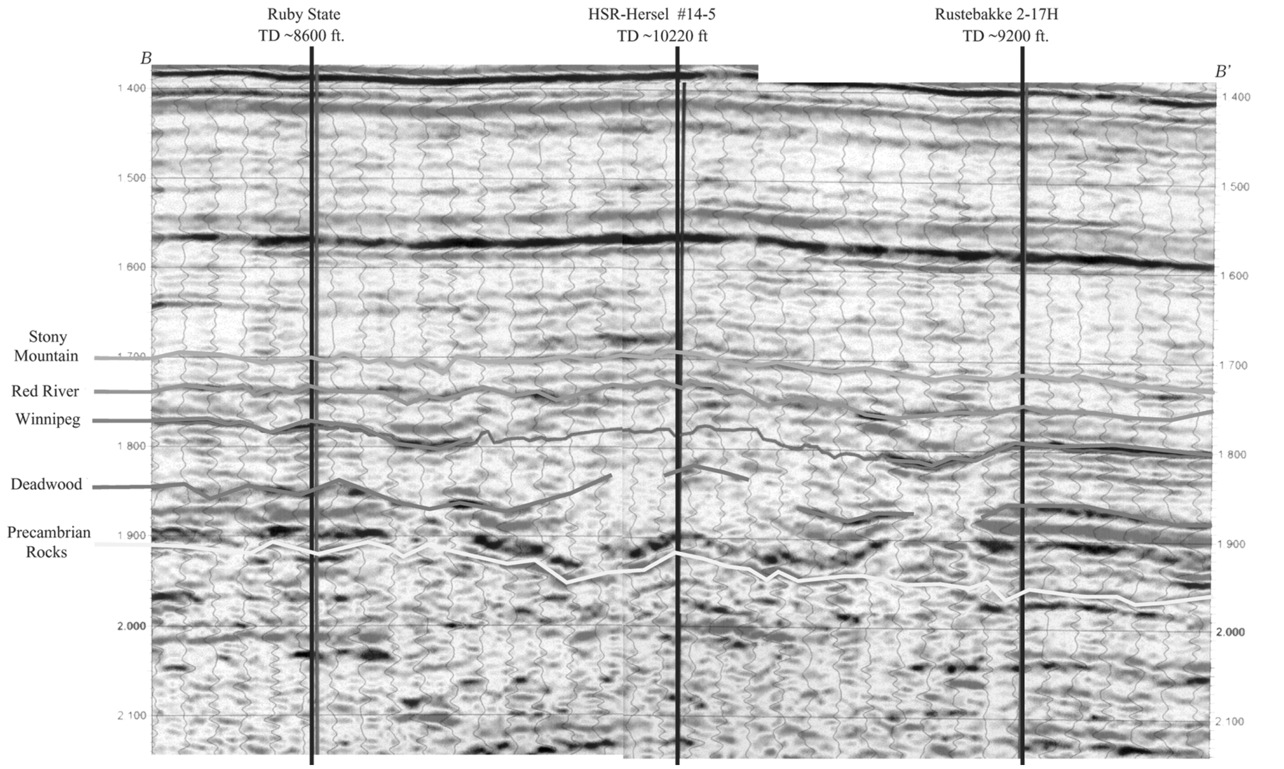

Fig. 7. 2D seismic profile across Peerless structure (cross section line shown on Fig. 5). Interpreted formation tops are shown. The vertical scale is two-way time traveled in seconds; velocity varies with lithology. The Ruby State, HSR-Hersel #14-5, and Rustebakke 2-17H locations, running west to east, are identified. (Courtesy of HS Resources)

recognized. The criteria are grouped into four categories: 1) surface form and geologic structure; 2) geophysical characteristics; 3) general characteristics of bulk rock types and their geochemical composition; and 4) microscopic deformation and melt features. Since the Peerless structure is buried under ~2700 m of sedimentary deposits, some of the criteria, especially the first, cannot be evaluated.

Geophysical Characteristics

Analysis of the Peerless 3D seismic map and 2D profiles reveals a regional stratigraphic interruption by the structure, with normal depositional patterns present outside the structure. The general chaotic appearance of the seismic reflectors is corroborated by the higher resolution well log data and pervasively brecciated rock seen in the well cuttings.

Some impact structures now being discovered are buried and geophysical evidence has become a primary source of evidence of extraterrestrial impact origin. Seismic data is expensive and obtained primarily by the oil and gas exploration industry. Many impact structures have not only been found by this method but have become economic resources for the companies that found them.

Bulk rock types are grouped into three general categories: 1) monomict breccias; 2) polymict breccias; and 3) melt rocks.

Monomict Breccias

Evidence of intense brecciation can be seen within autochthonous rocks of the structure.

Polymict Breccias

The presence of heterolithic breccia seen in the cuttings could possibly qualify as polymict breccia. The brecciated layers do appear to have occurred at once with some showing distinct petrographic deformation and mixing of heterolithic rock fragments.

Geochemical Data

The presence of an enrichment of elements such as iridium has become very important in the identification of impact structures since iridium is rarely concentrated by other Earth-bound processes. Samples from the disrupted areas in both wells underwent gamma-gamma multiparameter coincidence spectrometry after neutron irradiation at the Institute of Geochemistry, University of Vienna (C. Koeberl, personal communication). The amounts recorded in this analysis proved to be, more or less, background values for crustal rocks and have been assigned no significance.

Lateral Extent of Rock Types

Because of poor well control at appropriate depths outside of the Peerless structure, the presence or absence in adjacent areas of anomalous rock types, such as polymict breccia or possible ejecta material, cannot be verified. With only two wells in the region penetrating to the depth of the structure and the rocks examined being well cuttings, the evidence of any breccia dikes or sills beneath the structure or other irregular horizontal layers such as melt-bearing rocks were difficult to identify. Neither igneous rocks nor anything that could be interpreted as melt were found in cuttings from either of the wells that penetrated the structure.

Unique Mineral Deformation Features

Microscopic shock deformation features found in rocks and their minerals are the primary means of confirming that a structure resulted from the impact of an extraterrestrial object. Planar deformation features and planar fractures in quartz grains are the principle criteria. The presence of diaplectic glasses or other high pressure mineral polymorphs are also used in verification of an impact origin. Unfortunately, the finding of such distinctive features at many sites has proven to be very difficult. For example, at the Red Wing Creek (North Dakota) crater, 700–800 grains of quartz were viewed before finding one grain that had distinctive PDFs (C. Koeberl, personal communication). Planar fractures or possible poorly developed PDFs, which occur in quartz grains from both wells, were indexed to determined their crystallographic orientation and frequency (Fig. 8). In the central uplift, the planar fractures appeared highly decorated or partly annealed and consist primarily of basal Brazil twins (0001) in grains from about 60 m below the crater floor (B. French, personal communication). Other prominent orientations were measured at {11$\bar{2}$2}/{2$\bar{1}\bar{1}$2}, {10$\bar{1}$1}/{0$\bar{1}\bar{1}$1}, {11$\bar{2}$1}, and {51$\bar{6}$1} using a U-stage microscope. These orientations are the same as those within shock-metamorphosed quartz from other documented sedimentary target impact craters (e.g., French et al. 1974).

Selective Mineral Melting

No evidence of mineral melt exists in the Peerless structure. However, with primarily a carbonate target rock, the expected volume of identifiable silicate impact melt within semi-autochthonous target strata and fallout material would be low.

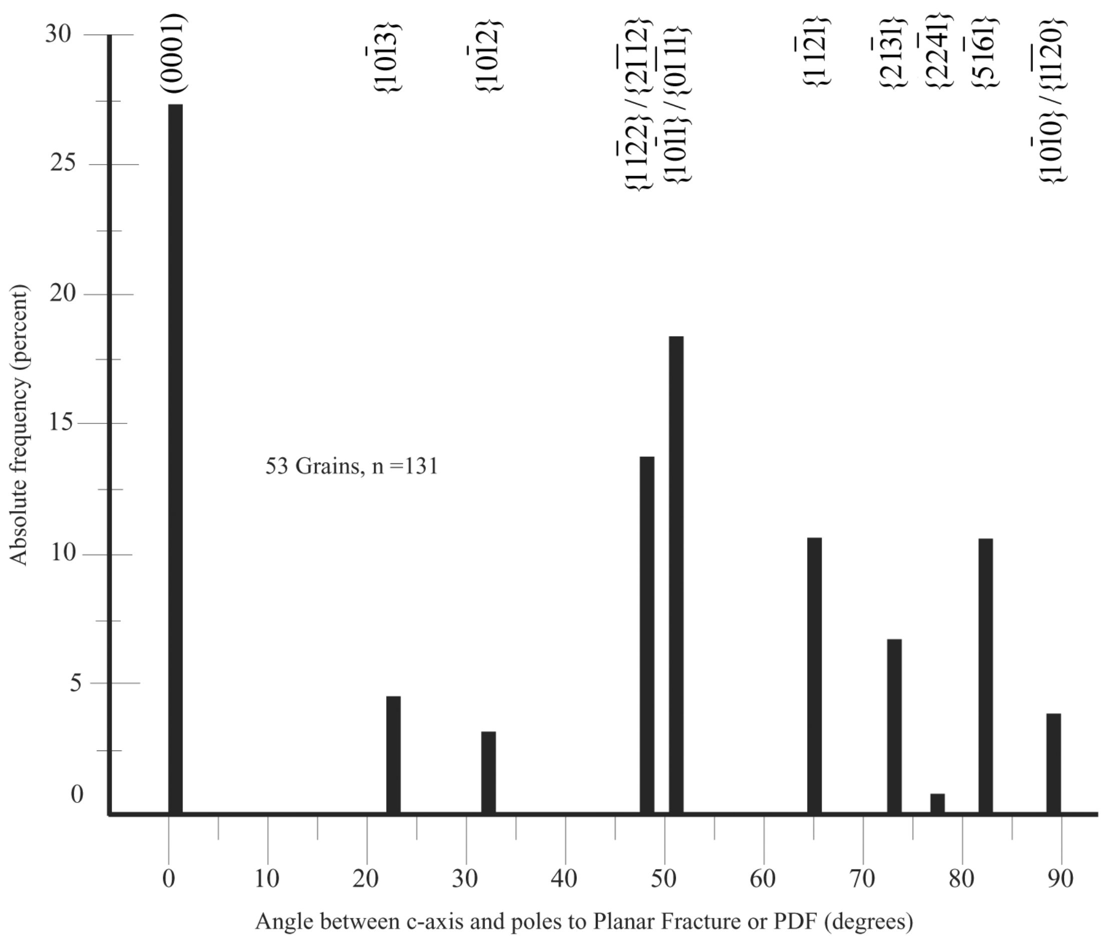

Fig. 8. Indexed planar fractures and possible PDFs in shocked quartz, based on combined data from HSR-Hersel #14-5 and Rustebakke 2-17 well cuttings. The indexing method is based on Grieve et al. (1996). The data are based on 143 measurements of 53 grains (unindexed n = 12).

Unusual Heterogeneous Glass Fragments

Based on the age of the Peerless structure at approximately 430–450 Ma, the presence of glass is unlikely, and none was found in the reviewed samples. Diagenetic processes would have reduced the glass to clays within a geologically short period of time.

CONCLUSION

The purpose of this study was to determine whether or not the Peerless structure is of extraterrestrial origin. Four other probable formation processes—volcanic activity, salt diapirism, monadnock draping, and channel formation or karstification—were investigated and excluded. Based on criteria for confirmation of impact craters and the evidence presented here from various forms of reviewed data including well logs, cuttings, petrography, 3D seismic maps, and 2D seismic profiles, it is reasonable to conclude that the Peerless structure may have been produced by an extraterrestrial impact.

This probable impact event, which occurred at ~430–450 Ma into shallow-marine sediments of the upper Ordovician Red River formation, is evidenced by a buried, complex crater consisting of an uplifted outer rim of ~6 km in diameter, an annular syncline of ~4 km in diameter, and a central uplift of ~2 km in diameter showing a vertical structural displacement of up to 90 m. The impact event affected the Ordovician to Cambrian lower Red River, Winnipeg, and Deadwood formations, and the underlying upper Proterozoic crystalline rocks. Post-impact crater fill, possibly deposited within a restricted marine embayment formed by the crater rim, is evidenced by an anomalous, localized kerogenite unit overlying both brecciated rocks of the central uplift and layered strata near the inner wall of the outer structural rim. Post-event wave reworking of the crater rim material, either by normal, shallow-marine processor or catastrophic breaching, may be evidenced by a unique, well-sorted, coarse sand layer preserved in the upper Ordovician Stony Mountain formation, which was deposited over the crater rim and adjacent area after impact. The regional effects of the probable impact, including the extent and nature of expected impact ejecta or tsunami deposits outside the crater, are presently unknown due to the lack of well data and outcrops away from the impact site.

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