

# WYOMING BATTERED WITH IMPACT STRUCTURES: SECONDARY CRATERING ON EARTH.

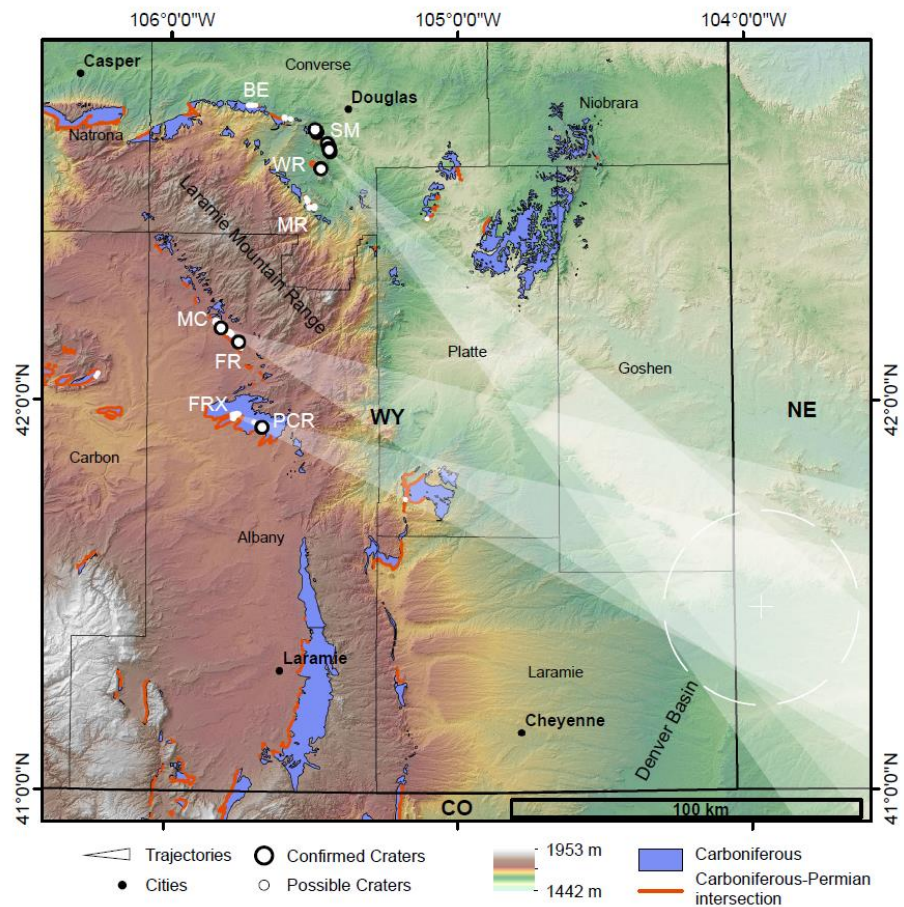
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**Introduction:** A field of small impact structures was reported in Permian strata of the Sheep Mountain anticline that is part of the Rocky Mountains Front Range system near Douglas, Wyoming [1]. Kenkmann et al. [1] reported a minimum extent of this crater field of 7.5 km by 1.5 km and identified more than 40, roughly circular to ellipsoidal possible impact structures therein. They interpreted this cluster of craters as an impact crater strewn field that was formed by the break-up of a single meteoroid.

**Results:** *Field work, remote sensing and petrography:* Since the discovery of the craters near Douglas, additional craters have been identified on the Sheep Mountain Ridge (SM) and along other outcrops of the same strata in southeastern Wyoming labeled BE, WR, MR, MC, FR, FRX, PCR in the Figure. We used satellite images with spatial resolution of ~ 0.3 m for identification of the crater structures. Many of the craters have been mapped with drones to ~ 0.05 m. The expanded area in which small impact craters could be confirmed now measures approximately 90 km in north-south and 40 km in east-west direction. The city triangle Casper, Douglas, and Laramie borders the crater field (Fig.). We call it the Wyoming impact crater field. This cratered area is too large to be explained by the atmospheric break-up of a meteoroid. Within this area we document 31 crater structures of 10-70 m diameter with shock features but without meteorite relics and more than 60 possible craters, where shock evidence is awaiting. We found both Planar Deformation Features (PDFs) and Planar Fractures (PFs) in quartz grains, of various crystallographic orientations. PDFs in the basal orientation (0001) are most frequent. Several shocked grains show multiple sets of PDFs. Some of the craters show chert layers associated with ejecta. Lumps of chert contain spheres of about 1

mm diameter that fulfill the characteristics of accretionary lapilli.

The mean crater diameter and mean crater ellipticity (aspect ratio) of the 90 confirmed and possible impact structures are 33 m, and 1.2, respectively [2]. All craters occur along the outcrops of the uppermost Permian-Pennsylvanian Casper Sandstone Formation and are approximately 280 Myr old. Their spatial arrangement shows clusters and ray-like alignments. Their partly preserved ejecta blankets show, in two cases, indications of herringbone pattern. Numerous craters have elliptical to ovoid crater morphologies that allow the reconstruction of impact trajectories. We used the suitable craters to define fan-like corridors of trajectories for the detected craters. Tracing back the trajectories we found that all trajectories meet in a single area that is at 150-200 km distance from the observed craters (Fig.). The radial arrangement of the trajectories suggests that the craters are secondary craters formed by ejecta from a primary crater. The intersection of the



trajectory corridors defines a polygon whose center is located at 41°28'N and 103°59'W.

**Modeling of ballistic trajectories:** We calculated ballistic paths of ejecta with 1, 2 and 4 m radius considering ejection angles from the hypothetical primary crater ranging from 30 to 60 degrees and initial speeds of 1, 2 and 4 km/s. Aerodynamic drag and Earth's curvature were taken into account. We used the Bernoulli drag equation and assumed that the ejecta boulders are spherical and do not break apart. The density of the atmosphere near Earth's surface was set at 1.204 kg/m<sup>3</sup>. We have not considered possible different atmospheric density profiles during the Permian. The ballistic range of 150-200 km from the primary, where we found the small craters, is not reached by 1 m radius ejecta. Of the 2 m radius ejecta, only those launched at 4 km/s reached the distance, where the craters are observed. Larger blocks of 4 m radius ejecta that left the primary at a speed of 2 km/s also fall in this ballistic range [2]. The impact velocities of these ejecta range from 500 to 1000 m/s and depend on the ejection angle. The impact energies of these ejecta range from about 12 to 400 GJ. The ratio between impact energy and initial launch energy ranges from 10 to 25% for ejecta landing at the range, where the secondary craters have been found, while their impact angles range from 45 to 60°.

**Modeling secondary craters:** To link the ballistic trajectories and impacting ejecta with crater formation the resultant craters were modeled using the iSALE shock physics code. Modifications to the original SALE code [3] include an elasto-plastic constitutive model, fragmentation, various equations of state (EoS), a modified strength model, a porosity compaction and dilatancy model [4-8]. We used EoS for quartzite [9] and considered porosity [7]. We determined the expected size of the craters formed by projectiles of 1, 2, and 4 m radius, travelling at velocities between 500 and 1500 m/s. Additionally, we determined the mass of material that experiences shock pressures greater than 3 GPa, the minimum pressure required for the formation of shock metamorphic features in quartz. The results of the iSALE simulations demonstrate that impactors of 1, 2, and 4 m radius, travelling at velocities between 500 and 1500 m/s, are capable of generating craters that are 8 – 55 m in diameter. The depth-to-diameter ratio of these craters ranges from ~0.125 for 500 m/s impacts up to ~0.25 for 1500 m/s impacts. Impacts at 500 m/s generate no material shocked to pressures greater than 3 GPa. Impacts between 500 m/s and 1000 m/s generate between 0 and 10% of shocked material of the impactor's mass, and impacts at velocities greater than ~1000 – 1250 m/s (depending on target material) will

generate significant, though still small, masses of shocked material (>10% of the impactor's mass).

**Discussion:** We have discovered several crater clusters in SE-Wyoming located in the uppermost Casper Fm in transition to the Goose Egg Fm. Due to their stratiform occurrence we infer that all craters were formed at the same time about 280 Myr ago in a single event. Secondary cratering appears to be the most plausible mechanism to explain the clustering and the crater characteristics. Observations that support the secondary cratering model are: (i) The elliptical crater morphologies allow the reconstruction of trajectories that meet in a single area. (ii) The relative abundance of elliptical crater morphologies and partly irregular crater shapes suggest relatively low impact velocities, which is compatible with secondary crater formation. (iii) The presence of radial crater chains and crater clusters that we observe is also known from secondary craters formed on the Moon or Mars. (iv) The absence of meteorites in the Wyoming crater field is compatible with an ejection process from a primary crater as the cause of crater formation. (v) The presence of possible accretionary lapilli mixed with the ejecta of the small craters indicates that a presumably hot ejecta plume existed and interacted with the local ejecta distribution. (vi) Linear ejecta accumulations are interpreted as the remnants of possible herringbone patterns formed by the interaction of ejecta of the primary and secondary cratering process. (vii) The calculations of impact trajectories reasonably match the conditions for the formation of craters ranging from 10 m up to 70 m at 150-200 km distance from the proposed primary crater. (viii) The small crater volumes exceeding a 3 GPa shock level are in agreement with the limited amounts of shocked minerals found in the craters.

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**References:** [1] Kenkmann, T. et al. (2018) *Scientific Rep.*, 8, 13246. [2] Kenkmann et al. (2022) *GSA Bull. (in press)*. [3] Amsden, A. et al. (1980). *Los Alamos Nat. Lab. Report, LA-8095*. [4] Melosh H.J. et al. (1992) *JGR.*, 97, 14,735–14,759. [5] Ivanov B.A. et al. (1997) *Int. J. Impact Eng.*, 20, 411–430. [6] Collins, G.S et al. (2004) *Met. Planet. Sci.*, 39, 217–231. [7] Wünnemann K. et al. (2006) *Icarus*, 180, 514–527. [8] Collins, G.S. (2014) *JGR*, 119, 2600–2619. [9] Melosh, H.J. (2007) *Met. Planet. Sci.*, 42, 2035–2182.