Al Hawi, a 4-km wide-impact structure in northern Saudi Arabia

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Abstract
The northern region of Saudi Arabia hosts several impact craters and structures. This paper describes the discovery of a 4-km-wide complex impact structure located in the paleozoic sedimentary rocks of northern Saudi Arabia 210 kilometers north east of the city of Tabuk. The impact structure is composed of a central peak displaying intense folding and shock metamorphism surrounded by an inner ring of mountains followed by a wider outer ring. The presence of shocked quartz displaying planar deformation features(PDFs) along with polymict breccia, micro-faults, steep folding and stratigraphic deformation suggests the structure was created by an extraterrestrial impact event.

Introduction
Impact structures are the most common geological structure in the solar system however due to earth's active geology and weathering processes's less than 200 terrestrial impact craters have been discovered. Impact structures are geological structures that form due to extraterrestrial impacts from asteroids or comets . As an asteroid or comet collides with the earth it immediately vaporizes surrounding rocks and subjects the area to a large amount of heat and pressure causing brecciation, folding,melting and shock metamorphism. Impact structure morphology consists of a circular shape as well as a central peak for complex craters. Due to their often eroded state, shape alone is not sufficient to prove a structure is of impact origin. To prove a geological feature is of an impact origin some criteria should be met including shock metamorphism such as planar deformation features in quartz, shatter cones and breccia however depending on the impact size, age and erosion some of these features may not be present (Kenkmann et al., 2014). 43% of impact structures are formed in sedimentary rocks however much remains unknown in the effect lithology and bedding has towards the final impact structure (Sahoui, 2024). The newly discovered impact crater described in this paper which is located in sedimentary rocks will help give insight into the processes and variables that shape impact structures that form in this geological setting.

Methods
The first stage of the search for terrestrial impact craters was a satellite survey of the Kingdom of Saudi Arabia, after a circular feature was identified at the coordinates 29°27'17"N 38°21'25"E near the Tabuk-Al Jouf province border, an expedition was led to the impact structure. Rock

samples and sand samples were collected from beyond the visible edge of the crater, the central peak, the inner ring, the outer ring and the crater floor.

Sample Sites	**Coordinates**	**Sample Number**	**Coordinates**
Site 1	29°25'46"N 38°22'41"E	**Site 16**	29°27'04"N 38°21'31"E
Site 2	29°25'46"N 38°22'43"E	**Site 17**	29°27'06"N 38°21'31"E
Site 3	29°25'48"N 38°22'40"E	**Site 18**	29°27'06"N 38°21'31"E
Site 4	29°26'25"N 38°21'19"E	**Site 19**	29°27'07"N 38°21'32"E
Site 5	29°26'31"N 38°21'26"E	**Site 20**	29°27'08"N 38°21'29"E
Site 6	29°26'41"N 38°21'26"E	**Site 21**	29°27'10"N 38°21'27"E
Site 7	29°26'41"N 38°21'24"E	**Site 22**	29°27'22"N 38°21'28"E
Site 8	29°26'48"N 38°21'35"E		
Site 9	29°26'48"N 38°21'36"E		
Site 10	29°26'51"N 38°21'38"E		
Site 11	29°26'53"N 38°21'47"E		
Site 12	29°26'55"N 38°21'50"E		
Site 13	29°27'00"N 38°21'43"E		
Site 14	29°27'04"N 38°21'36"E		
Site 15	29°27'03"N 38°21'30"E		

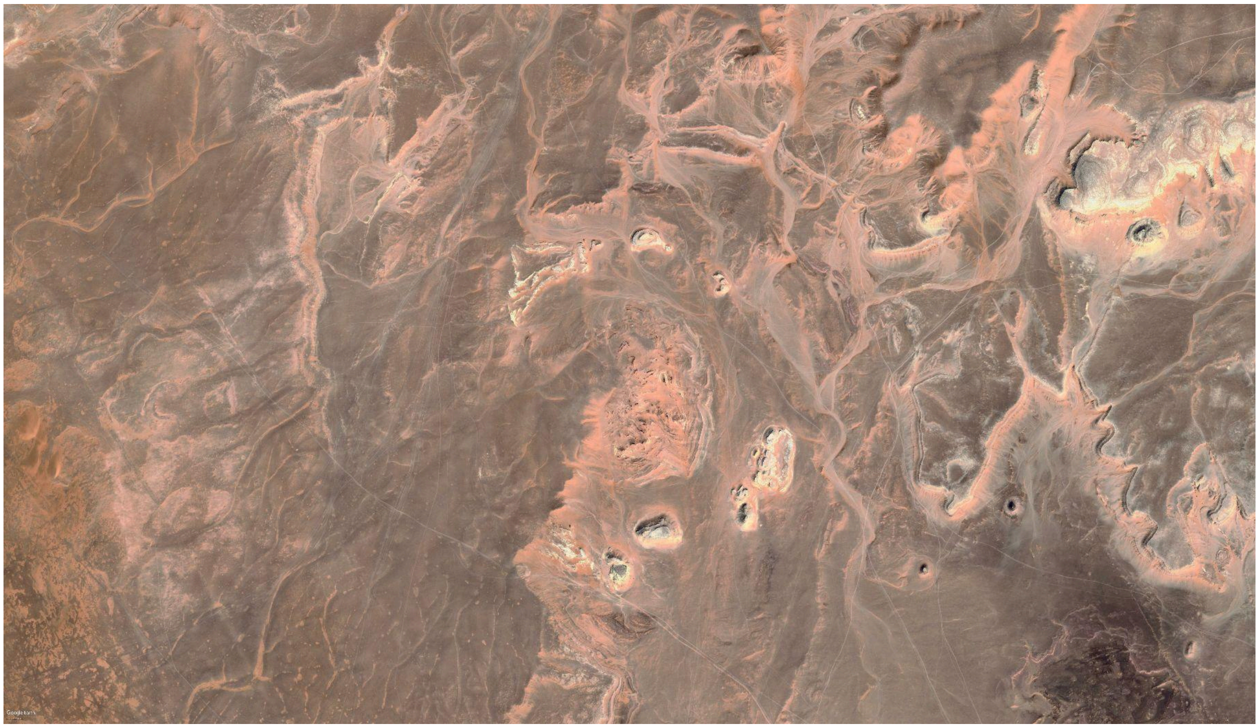


Figure 1: A satellite image of the impact structure showing the central peak surrounded by the white inner ring followed by the eroded outer rim. The western third of the structure is buried beneath recently deposited quaternary gravel sheets.

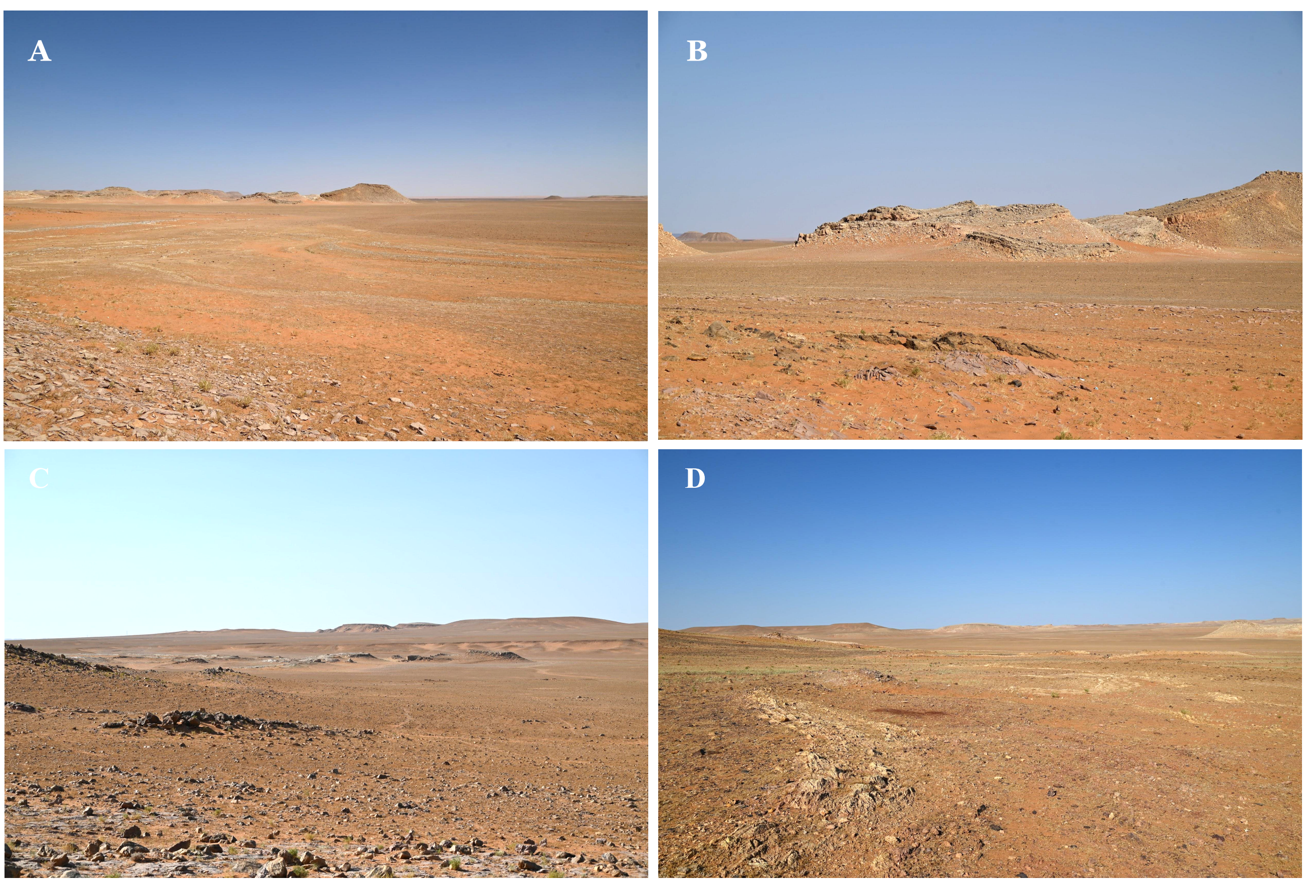


Figure 2: (A): Photograph from the central peak facing south showing the inner ring of mountains and the highly folded floor of the central peak. (B): White inner ring of mountains displaying folded strata. (C): View from the central peak facing north showing the northern section of the white inner ring of mountains with the surficial quaternary deposits behind them burying the rest of the structure. (D): Steeply plunging folds in the central peak.

Figure 3: (A): Minor faults present on the floor of the central peak. (B): potential shatter cone structures. (C) : Fractured sedimentary rock. (D): Fractured sedimentary rock in the inner rim. (E): Globules of rounded quartz crystals embedded in the host rock. (F): Polymict impact breccia.

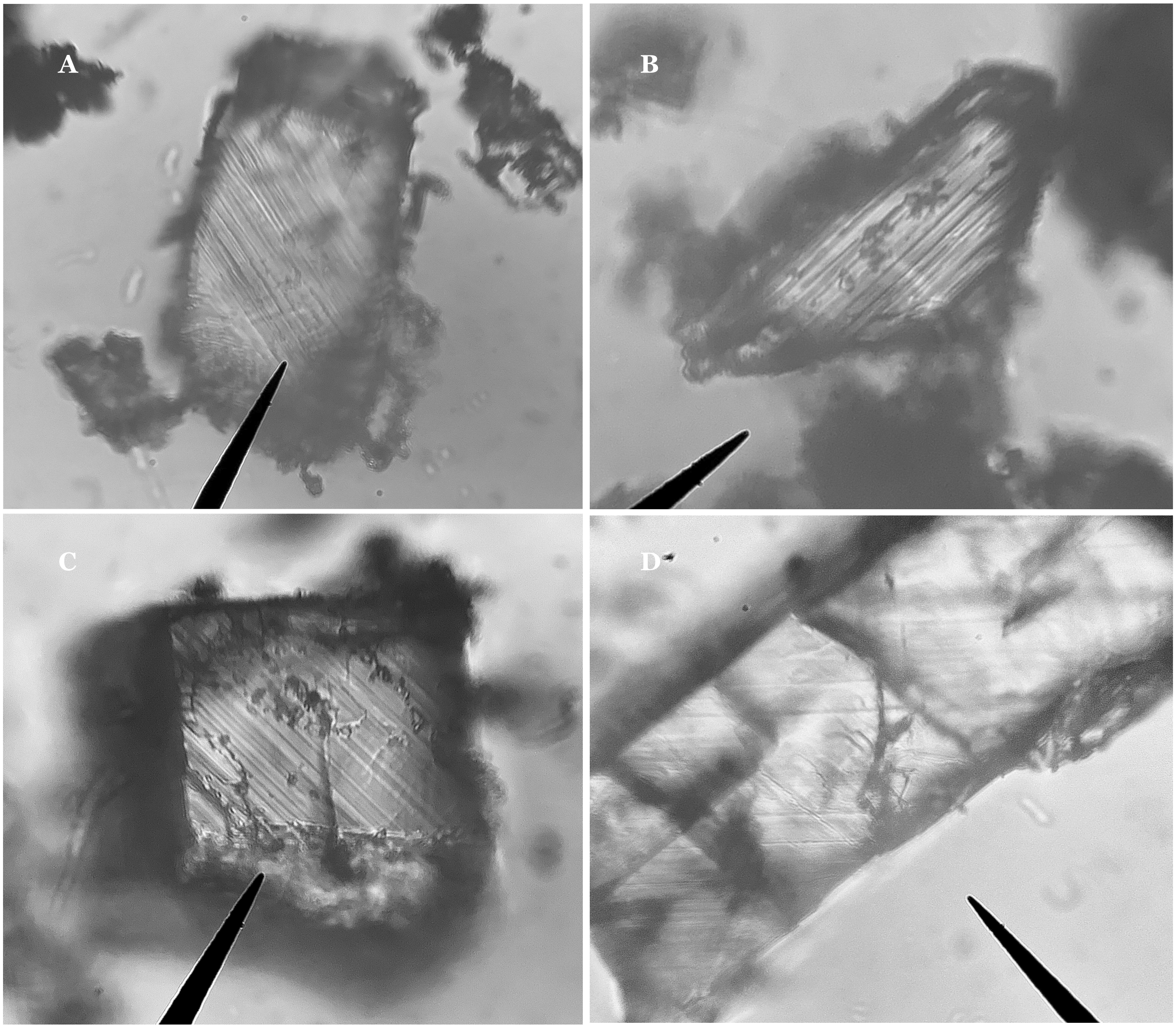
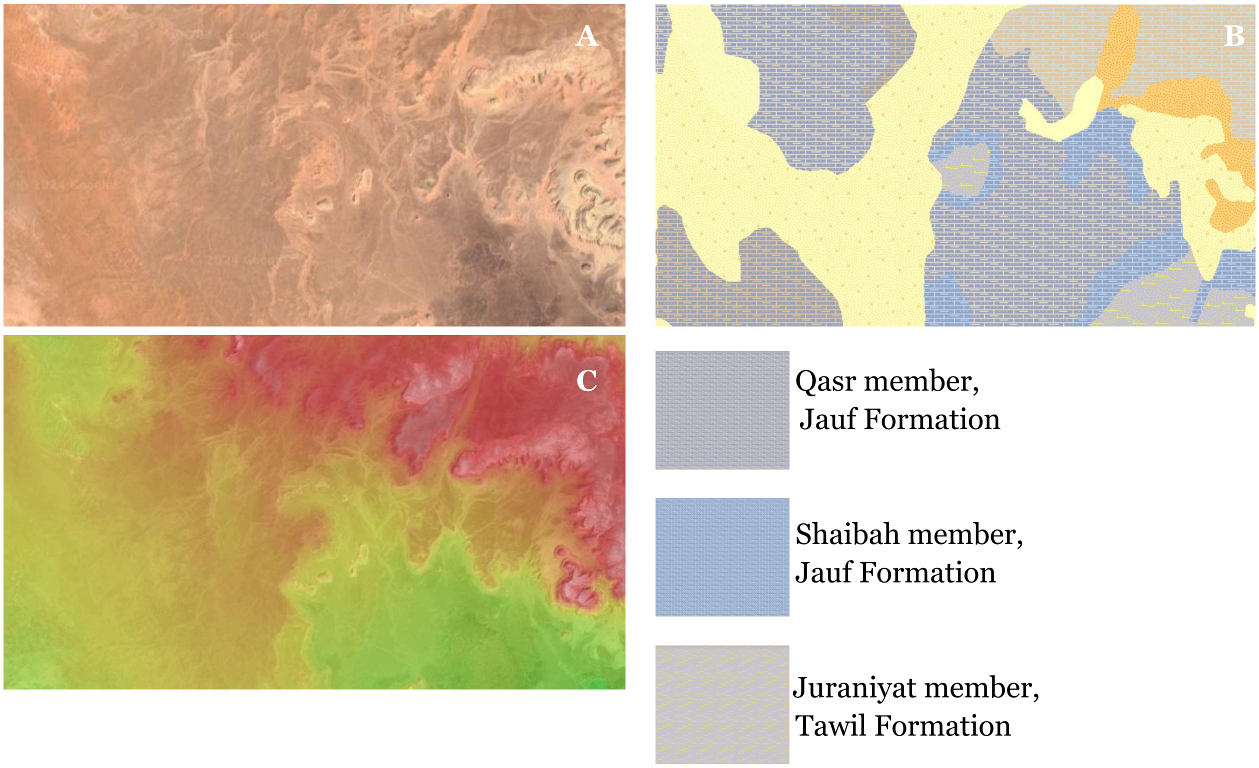


Figure 4: photomicrographs of shocked quartz grains displaying planar deformation features created by high pressure shock metamorphism.

The search for shocked quartz was conducted through sediment sampling throughout the impact structure however due to the highly eroded nature of the structure no shocked quartz was found from surface sand samples. This is due to the small size of the impact event only producing shock metamorphic effects to a limited depth and range, and the erosional depth has exceeded the depth limit of the shock metamorphism in most locations. The only location in which shocked quartz was found was from grounded quartz rocks from the folded strata of the central peak[FIgure3, site F(29° 27 '04"N 38° 21' 35"E)] . The central peak consists of material that was initially in close proximity to the impactor and underwent the greatest amount of pressure and metamorphism. The central peak is also more resistant to weathering and remains the tallest peak in the structure also aiding in the preservation of rocks hosting shocked quartz.



The stratigraphy of the paleozoic sedimentary basin of the northern region of Saudi Arabia has been well described (Al-Husseini & Matthews, 2006) being composed of marine sediments ranging in age from the Cambrian to Devonian period. The sedimentary rocks in which the impactor collided with is of devonian age and what remains today after heavy erosion is the Juraniyat member of the Tawil Formation overlaid by the Shaiba member of the Jauf Formation followed by the Qasr member of the Jauf Formation. In the surrounding area these members remain in their original sequence parallel to the ground, however the impact event caused a rebound of the deeper older Juraniyat member of the Tawil Formation elevating it higher than the more recent rocks as seen in the geological map (B) created by the Saudi Geological Survey. This rebound effect has caused the oldest rocks to be exposed in the center surrounded by rings of progressively newer rocks.

Due to the impacted rocks being roughly 400 million years old, the impact event must have happened less than 400 million years ago. Taking into account the heavy erosion sustained by the structure, it is likely older than 2 million years thus yielding an age estimate of 2-400 million years old. Further chemical analysis must be conducted to increase the accuracy of the age measurement.

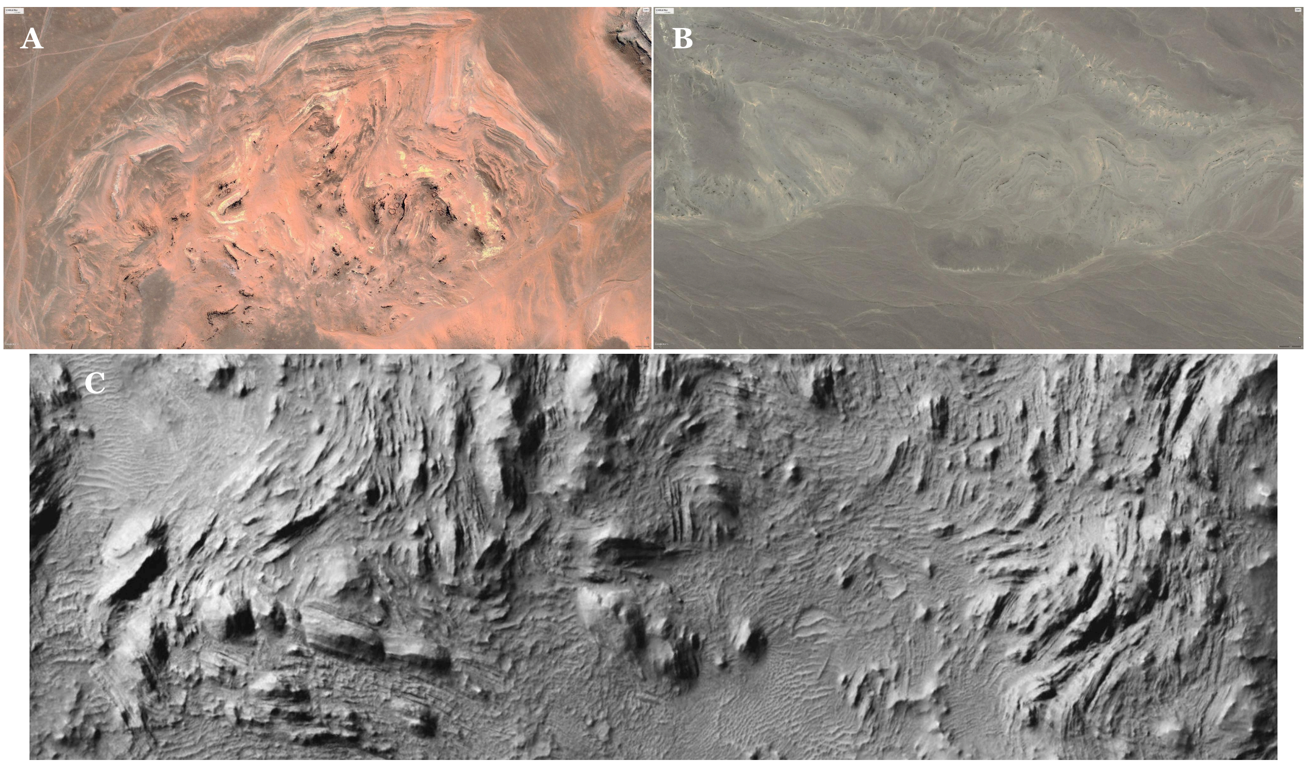


Figure 5: (A): A satellite photograph of the intense folding of sedimentary rocks in the central peak area of Al Hawi impact structure(Google Earth). (B): Similar >90° folds in the strata of sedimentary rock layers near the center of Jabal Rayah impact structure 145 km south west of Al Hawi crater near the city of Tabuk (Google Earth). (C): Intense folding of sedimentary rocks in the central peak of Martin crater in Fellis Dorsa, Mars (NASA/JPL/MSSS/The Murray Lab) . (**Note:** The folds in these photographs are not to the same scale with the largest being figure C, then A followed by B. However the mechanisms of their formation remain the same).

The size of the impactor that created this 4-km wide crater remnant can be determined using calculations developed by (Collins et al., 2005). However due to multiple variable factors there is a range of possible combinations of impactor sizes, speeds and compositions that could have all created the 4 kilometer wide crater.

1: Projectile density: Porous rock(1500 kg/m3) Velocity: 17 km/s (average asteroid velocity)	Impactor diameter: 350 meters
2: Projectile density: Porous rock(1500 kg/m3) Velocity: 51 km/s (average comet velocity)	Impactor diameter: 220 meters
3: Projectile density: Dense rock(3000 kg/m3) Velocity: 17 km/s (average asteroid velocity)	Impactor diameter: 245 meters
4: Projectile density: ice: (1000 kg/m3) Velocity: 51 km/s (average comet velocity)	Impactor diameter: 270 meters

Table 2: The 4 most likely combinations of projectile density and velocity assuming constant 45° entry angle.

The measurements shown in **table 2** yields an impactor diameter between 220-350 meters. Further chemical analysis must be conducted in the future to determine the type of asteroid or comet which will increase the accuracy of the projectile diameter measurment. It should be noted that the diameter of the original impact crater is likely much larger than 4 km however the true size of the original impact crater can only be determined through more extensive subterranean mapping, this would also imply the possibility of a much larger impactor.

Discussion

This paper describes the discovery of a 4-km-wide impact structure in northern Saudi Arabia near the city of Tabuk. This structure hosts enough evidence such as shocked quartz, polymict breccia, fractured rocks, steep folding, micro-faults and stratigraphic deformation to confirm its origin as an impact crater. It was formed by an asteroid or comet ranging from 220-350 meters in diameter and is between 2-400 million years of age.

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