Definition of Shallow Subsurface Structure Around the Chicxulub Impact Crater Using Ground Penetrating Radar; John A. Grant, SUNY College at Buffalo, Earth Sciences, Buffalo, N.Y., 14222, Peter H. Schultz, Brown University, Geological Sciences, Providence, R.I. 02912, and J. Oscar Campos-Enriquez, Instituto de Geofisica, UNAM, Deleg. Coyoacan, 04510, Mexico City, Mexico.

A growing body of evidence indicates that the buried Chicxulub impact crater in northern Yucatan is closely tied to the global extinctions that marked the Cretaceous-Tertiary boundary (*e.g.*, 1-4). The present topographic expression of the crater is limited, however, to a somewhat circumferential zone of collapse sinkholes or cenotes located 70-90 km from the crater center (5, 6). Previous workers demonstrated this cenote ring intercepts and channels the generally northward flowing groundwater around the crater center, thereby forming an important regional hydrogeologic boundary (*e.g.*, 5-8). Goals of the present study include better understanding cenote origin and their possible reflection of subsurface structure/stratigraphy. Earlier efforts at resolving cenote origin were impeded by the remoteness of the area, paucity of outcrop, and relied heavily on access to existing wells and satellite data to locate cenotes and map nearby fractures over distances of 10's of meters (*e.g.*, 5-7). Our approach utilized a ground penetrating radar (GPR) as a means of delineating shallow stratigraphy along and adjacent to the cenote ring, thereby helping to place new constraints on its origin.

Any mechanism for development of the cenote zone karst requires the presence of interconnected conduits in the form of fractures or regions of increased hydraulic conductivity. The simplest means of initially forming such conduits involves a single episode of post-impact slumping or subsidence around the crater (5). Similarly, an episode of more regional tectonic activity (perhaps associated with formation of the nearby Ticul fault) could form the fractures (5). Cenote zone groundwater conduits could also be created by fracturing in the thinner rocks covering the exterior of the crater or by isostatic flexure caused by differential settling between the thicker rock sequences filling the crater and the thinner exterior rocks (5). Such flexure might have been aided by loading/unloading of water during sea level changes and could extend fractures formed by prior tectonic events through the entire crater filling sequence. Finally, conduits may form when primary dissolution in rocks with high hydraulic conductivity create a weakened area beneath overlying lithologies along the crater rim or wall. For example, early dissolution in thick ejecta beneath the cenote carbonates (5), in reef carbonates emplaced along the crater wall/rim (9) or in lateral/vertical variations in lithology emplaced along the crater wall/rim as sea level rose and/or fell could cause subsidence and fracturing.

To further explore these possible means of cenote ring formation, a fully digital GPR was deployed along transects across and outside the cenote ring to reveal subsurface reflectors corresponding to shallow stratigraphy. The nearly pure carbonate rocks covering the crater (10) are generally well-suited to probing with GPR: exceptions occur in those areas (primarily inland) where local accumulations of terra rosa soils rapidly attenuate the signal. Radar penetration on most stripped surfaces is equivalent and generally insensitive to the presence of extensive secondary calcrete deposits formed within ~5 km of the coast (8). Individual transects were completed using the GPR in a continuous mode and extended up to ~4 km in length. Both 500 MHz and bi-statically configured 100 MHz transducers were used to maximize vertical/horizontal resolution and locally define reflections at up to 10-12 m depth (assumes a radar pulse travel time of ~12 cm/ns). Data collected across the ring at Cenote Nochail to the northeast (relative to the crater center), Cenote Chunkana to the southeast, and along the ring near Cenotes Kaan and Nabula to the southwest reveal significant variations in the distribution of subsurface karst features, fractures, and the depth to (and possible thickness of) the fresh groundwater lens in coastal sections.

The changing character and distribution of reflectors observed in the GPR data collected along and outside the cenotes strongly suggest occurrence of enhanced weathering and karst development at the ring. Much of the ring-karst is caused by groundwater movement along fractures and likely creates interconnected open channels in the subsurface ranging in scale from granular to micro-cavern and cavernous (6). In the flat-lying coastal region northeast of Merida a distinct transition zone is identified using the radar. Shallow 500 MHz data from west to east across the cenote zone delineate numerous shallow-dipping reflectors and extensive cavernous karst (some voids are less than 1 meter below the surface) that decrease abruptly at a prominent marker. East of this transition the reflectors/bedding are more uniform and continuous corresponding to less extensive fracturing and karst. Data obtained in the cenote zone with the 100 MHz transducer delineate the extensive karst to depths of at least ~10 m and highlight its relatively continuous occurrence there. Karst detection at greater depth is precluded by the presence of a reflector that probably marks the base of the fresh groundwater. The relative paucity of extensive karst beyond the ring is intriguing given the mapped abundance of fractures (5,6) and their potential as groundwater conduits.

GPR data collected at the slightly higher elevation southeast of Merida reveals a ~10-15 m vadose zone above the generally northward flowing (6) groundwater. As a result, numerous deep cenotes pock-mark the surface along this portion of the ring. GPR and visual inspection of cenote Chunkana reveals large lateral air and/or water-filled caves that highlight the large scale cavernous weathering that can be associated with the cenotes. Limited GPR data and penetration depth suggests most observed near-surface fractures are related to partial collapse of cavern overburden and preclude detection of smaller scale karst below the water table. GPR investigation of the cenote ring SW of Merida places the water table at depths intermediate between the two sites described previously. Analysis of GPR data collected in this area with the bi-statically configured 100 Mhz transducer reveals that vadose zone karst is of intermediate abundance, but appears to be most common at the level of the present water table (approximately 8-9 m below the surface). The abundance of smaller scale karst features near the top of the phreatic zone in all three areas is expected if the evolution of the cenotes is ongoing. A somewhat lesser abundance of karst in the vadose zone suggests dissolution was less advanced during prior high stands of the water table.

These results demonstrate the utility of the GPR in mapping the water table, shallow karst, and distribution of near-surface fractures around the buried Chicxulub crater. Moreover, the data provide new insight into formation of the cenotes and helps distinguish between theories for their occurrence as a discrete zone. For example, a "one-time" tectonic origin of water conduits along the zone (*e.g.*, 5) requires rapid propagation of the dissolution horizon (located near the top of the phreatic layer, 11) during sea level/water level changes (*e.g.*, during the Pleistocene) and an absence of extensive secondary carbonate deposition. GPR data confirms that shallow karst is enhanced along the level of the present water table, but remains connected to flow at greater depth as evidenced by a salt water lens near the coast. Hence, we suggest these interconnected karst zones reflect dissolution along fractures maintained or episodically reopened during crater burial rather than vertically continuous dissolution along or above a single event fracture. In addition, the lesser extent of water-filled karst outside the cenote zone implies differential fracturing between thick and thin rocks in and outside the crater (*e.g.*, 5) is not solely responsible for ring evolution unless accompanied by sustained or episodic flexure along the ring. Otherwise, fractures outside the cenote zone should be marked by a similar development of water-filled karst, especially where their orientation approximates the north-south flow of regional groundwater (6). We suggest a more likely scenario for evolution of the cenotes may include flexure and enhanced fracturing along the ring that could sustain or reopen conduits created during a prior tectonic event(s). Such flexure/fracturing could relate to differential loading caused by differing sediment thicknesses inside and outside the crater or by rising/falling sea level. Early dissolution in a near-rim layer or sequence of enhanced hydraulic conductivity might also induce flexure/fracturing in overlying stratigraphy. Future work with the GPR should help identify whether such a layer or sequence exists and establish its lithology (*e.g.*, ejecta or reef carbonates).

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