Vertical Seismic Profiling of the Chicxulub Impact Basin Peak Ring

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Summary

Here we detail the vertical seismic profile (VSP) collected during Expedition # 364 of the International Ocean Discovery Project / International Continental Scientific Drilling Program (IODP/ICDP). The drilling target is the peak ring of the Chicxulub impact basin, suspected to be responsible for the K-Pg extinction event 66 Ma ago (Schulte et al. 2010). Seismic reflectivity is observed throughout the 1300 m VSP, most prominently from boundaries of major velocity changes; four major velocity regions were recorded within the borehole. Seismic wave speeds were observed to be very low in shock metmorphosed granite, nearly 2000 m/s less than expected for non-impact affected granite. Post expedition processing is currently underway with the goal of full wavefield separation of the VSP to generate a single seismic trace.

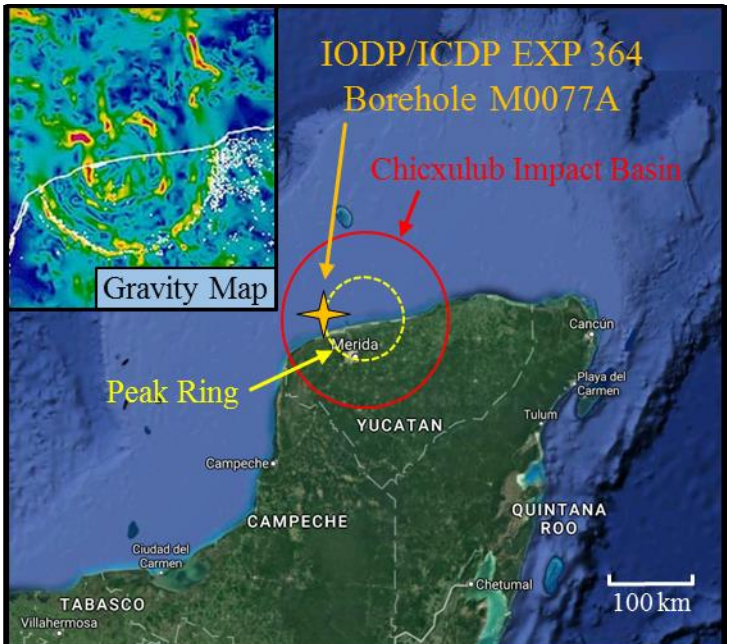

Figure 1. Project location on continental shelf in Gulf of Mexico. Borehole was drilled in the most prominent region of the peak ring structure (*modified from* Google Earth 2016). Upper left: Bouguer gravity anomaly map, showing concentric circular structure. Positive anomaly (Red), Negative anomaly (blue), Shore line (white), sinkholes (white dots) (Swarzenski 2003).

Introduction

The Chicxulub Impact basin and the associated K-Pg extinction event has piqued interest across many disciplines. Originally discovered by Penfield and Camargo while searching for petroleum deposits (Hildebrand et al. 1991), it has become scientific consensus in the following decades that the Chixculub Impact structure, created roughly 66 Ma ago at the K-Pg boundary layer, is likely associated with the associated mass extinction of 75% of all life on Earth, including the dinosaurs.

The Chicxulub impact basin has been extensively mapped; seismic, gravity, and magnetic surveys have been used to construct models of the impact basin and numerous boreholes have been studied within the structure as well (Gulick et al. 2013). Expedition 364 was motivated by questions in many disciplines: Paleomagnetists, nanopaleontologists, microbiologists, astrobiologists, geologists, and geophysicists all participated in pursuing two major questions: 1) How was life affected after surviving this major extinction event? Disaster taxa and biostratigraphy are key points, but an intriguing branch is seeking hydrothermophiles in the borehole of the structure; discovery of such unusual extremophile microorganisms could have strong implications for astrobiology deep below the inhospitable surfaces of other planets. 2) How does a peak ring form? Many models have been put forward (Collins et al 2016), but they are difficult to constrain without real data. To date, Expedition 364 is the first time the peak ring of a large impact structure has been scientifically drilled.

Analagous to the ripples in a drop of water, large craters can develop a central uplift and even larger craters develop a circular ring of mountains (see figure 1). Although common throughout the solar system, peak rings on Earth erode quite rapidly. Luckily, the Chicxulub impact occurred in the Gulf of Mexico which is both 1) geologically inactive and 2) a depositional basin. Thus, the Chicxulub impact basin was well preserved until present day (Gulick et al. 2013).

Organized and funded by IODP & ICDP, expedition 364 was a multi-disciplinary mission to drill, core, and analyze the peak ring of the Chixculub crater. Our research group provided the VSP acquisition and analysis which is commonly used to calibrate surface seismic data and as a quality control check against borehole logging instruments.

Methods

Downhole seismic records were obtained using the U of Alberta's digital Sercel Slimwave™ geophone chain. The tool string consisted of 4 individual triaxial sondes at 15 m spacing for a total tool string length of 45 m. Borehole M0077A was drilled offshore in three phases to a total depth of 1335 m below sea floor (mbsf). After each drilling phase, the seismic team acquired zero-offset vertical seismic profiling (VSP) data in the newly drilled open hole portion prior to casing. The seismic source used was a 30/30 in^3 dual solenoid airgun provided by the U of Texas – Austin. Seismic records were recorded at a 250 μs sample rate for 3 seconds.

The tool string would be lowered to a predetermined depth, locked in place, then the airgun fired which simultaneously triggered recording. From this, a single seismic trace is generated for each geophone. Shots were repeated at each depth a minumum of 5 times in order to stack and improve signal to noise ratio. After recording a trace for each depth, all stacked traces on one axis can be combined into a composite VSP (see figure 2a). The sonde spacings along the borehole ranged from 1 m to 5 m, the spacing being influenced by rig time requirements during each of the 3 acquisition episodes.

Results

The VSP collected shows many prominent reflectors (figure 2a), the strongest at ~600mbsf, which corresponds to the boundary of the target peak ring and post impact sediments. From the first arrivals in the first VSP waveform, it is possible to assign least squares linear fits to 4 distinct velocity regions (figure 2b) (Schmitt et al 2007). With the exception of velocity zone three, the confidence bounds are high. Geologic core is not available above 500 m, but we suspect that the velocity increase of 282 m/s between zones 1 & 2 is due to an increase in lithification/compaction and not a compositional difference. Progression from velocity zone 2 to 3 at 600 mbsf gives both a velocity increase of 403 m/s and a reduction in confidence by 17 m/s; This correlates closely with the transition from the layered post impact sediments to the chaotic melt bearing breccia on top of the peak ring (denoted as light blue & brown to purple, respectively, in figure 2c); this breccia is presumed to have undergone aqueous sorting. The peak ring breccia velocities agree well with the prediction of a 100-200 low velocity layer through full seismic inversion by Morgan (Morgan et al. 2011). The boundary of Zones 3 & 4 at 720 mbsf is closely associated with the greatest velocity increase of the VSP: 1266 m/s. Zone 4 is associated with peak-ring material that is a mixture of impact melt and blocks of granite that were emplaced during the impact (denoted as pink in figure 2c). The average P-wave velocity of 4236 m/s is much lower than the expected value of ~6000 m/s (Schmitt 2015). The bulk density, too, is only about 2400 kg/m^3 (Morgan et al 2016) which is significantly less than a value of about 2600-2700 kg/m^3 normally expected for granite (Fig. 3). Figure 4 shows differential p-wave velocities calculated with a rolling window and associated upper and lower confidence bounds; the velocities presented in figure 4 are well corroborated by fine scale peak ring velocity models developed by Morgan et al., giving a range of 3900-4500 m/s for the bulk of the peak ring material (Morgan et al. 2011). A prominent low velocity region appears from 250-280 m and is associated with a region of poor signal clarity in the full VSP waveform (fig 2a). A brief jump in velocity at 600 m is associated with an 11-m thick layer of limestone on top of the melt bearing breccias of the peak ring. Relative high velocity regions at 800 and 1100 m depth do not appear to be associated with distinct lithologic regions; this inhomogeneity may be due to the impact, but specific methods are presently unclear. Overall, the complex structure between 0 and 700m suggests layered lithologies affecting velocities, but the smoother structure below 700m depth suggests there may be a more homogeneous contribution to the low seismic velocities in the granites.

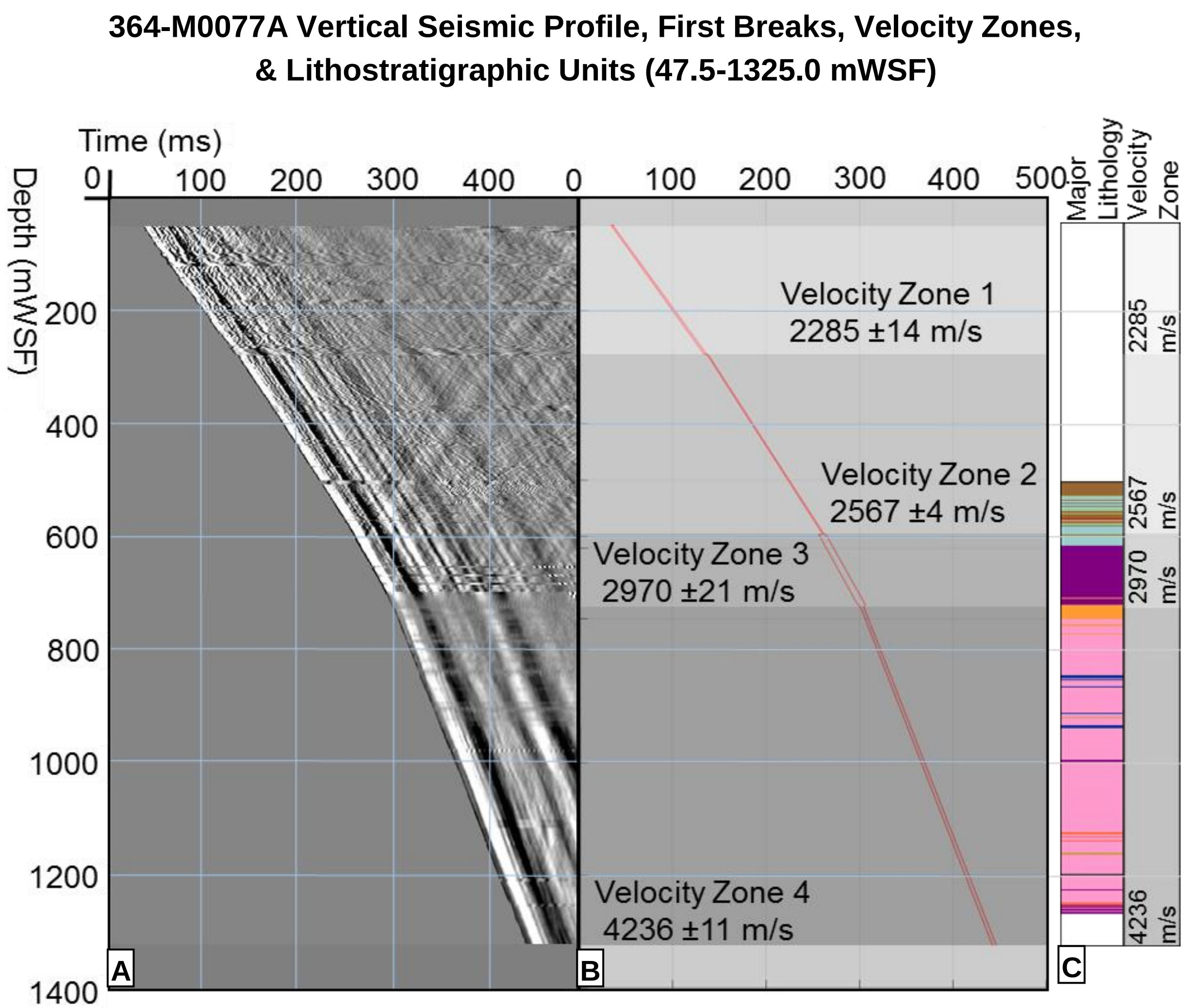

Figure 2. A) Full VSP Waveform. Shown with topmute. Loss of high frequency data at 700m is due to a technical problem and not a result of geology. B) Linear fit slopes are assigned to four major velocity regions, and shown with upper and lower confidence bounds. C) Lithologies are shown with depth and compared to velocity zone boundaries. Major units are: Granite (pink), Melt (orange), Breccia (purple), Limestone (aqua), Marl(brown).

Summary and Outlook

The digital downhole system used provided a good quality VSP and a clear picture of reflectors. Full wavefield separation is currently in progress and will be used to improve accuracy of the seismic tomography collected nearby (Gulick et al. 2013). Most intriguing is the unusually low basement seismic velocities; these may be due to porosity, microcracks, large scale fracture systems, or a combination of factors. The low velocities may as well be a result of a cause unmentioned yet.

Borehole M0077A: Sample 155 R2

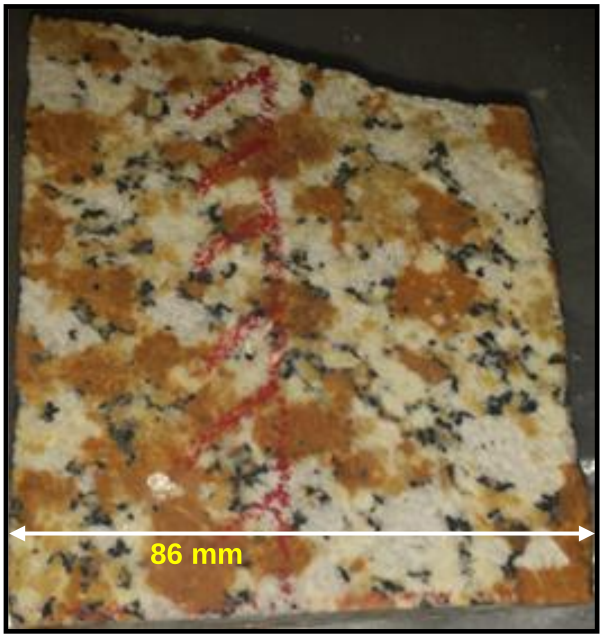

Figure 3. Typical basement granite sample. ~895m depth. Grains up to 10 mm diameter.

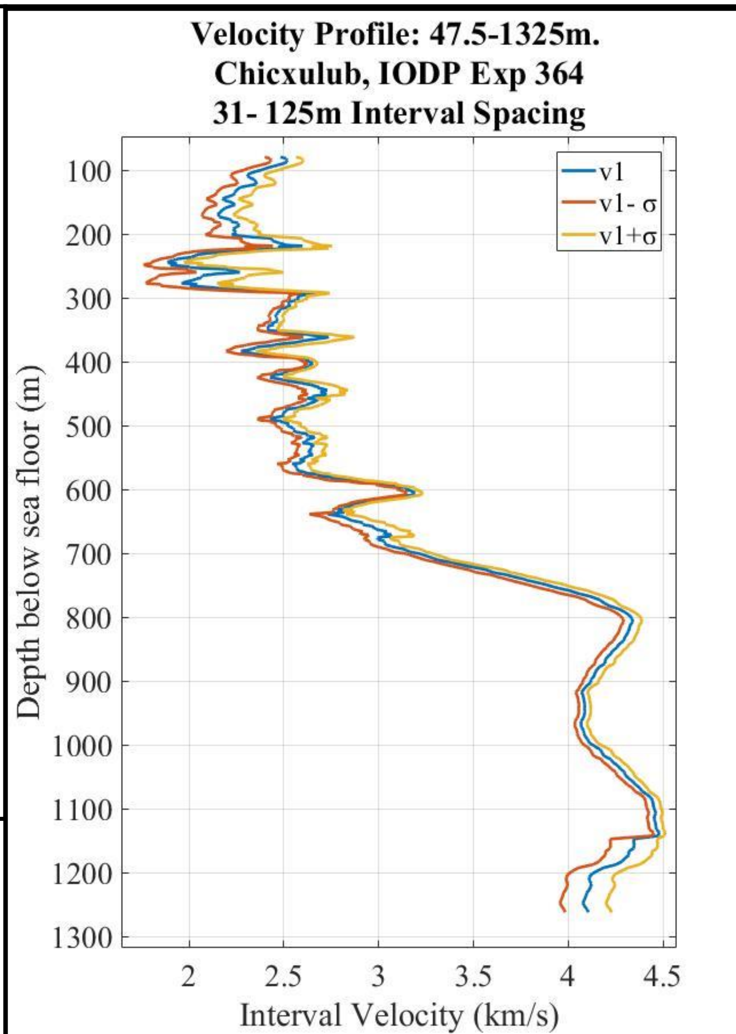

Figure 4. Differential P- Wave velocities (Blue) and Upper/Lower confidence (Yellow/Red). Calculated with moving window of 21 sample depths; sample spacing varied from 1.25-5m giving a moving window of 31-125 m.

Current work includes completion of full wavefield separation of the VSP, integration with previously completed surface seismic data, and laboratory analysis of ~10kg of half core sample recovered from various depths throughout the borehole. The 20 samples are mostly homogeneous in structure; 10 granite, and 10 melt. Testing of the samples includes porosimetry, pycnometry, and 4-axial p-wave travel speed under pressure up to 200 mPa. If microcracks are responsible for the low wave speeds, a strong increase in sample velocity should be seen with increase in pressure. However, if pores or large scale structure are responsible, then a weaker increase in wave speed with pressure will be seen. Anisotropy measurements will yield hints as to the nature of deformation and rearrangement of the Earth's crust from the Chicxulub impact, 66 Ma ago.

Acknowledgements

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