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Mantle deformation beneath the Chicxulub impact crater

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ABSTRACT

The surface expression of impact craters is well-known from visual images of the Moon, Venus, and other planets and planetary bodies, but constraints on deep structure of these craters is largely limited to interpretations of gravity data. Although the gravity models are non-unique, they do suggest that large impact craters are associated with structure at the base of the crust. We use seismic data to map Moho (crust–mantle interface) topography beneath the Chicxulub crater, the youngest and best preserved of the three largest known terrestrial impact craters. The Moho is upwarped by ~1.5–2 km near the center of the Chicxulub crater, and depressed by ~0.5–1.0 km at a distance of ~30–55 km from the crater center. A comparison with numerical modeling results reveal that immediately following impact a transient crater reached a maximum depth of at least 30 km prior to collapse, and that subsequent collapse of the transient crater uplifted target material from deep below the crater floor. These results demonstrate that deformation from large terrestrial impacts can extend to the base of the continental crust. A similar Moho topography is also modeled for some large lunar and Martian craters, which suggests that mantle deformation may play a prominent role in large crater formation.

1. Introduction

The morphology of impact craters changes with size, progressing from small simple bowl-shaped craters to large multi-ring craters (e.g., Gilbert, 1893; Dence, 1965; Hartmann, 1972; Schultz, 1976; Wilhelms et al., 1987; Melosh, 1989). The formation of small craters is fairly well understood from terrestrial field studies and laboratory tests, but the construction of large craters is not easily extrapolated from these observations since the kinematics of cratering change with size (e.g., Melosh, 1989). Thus it is essential to obtain constraints on the deep structure of impact craters in order to further our understanding of the formation of large impact craters.

Visual images from the Moon, Venus, and other planets and planetary bodies constrain the surface expression of different crater types, but provide no subsurface information. Gravity data over these craters offer some control on deeper crater structure; however, gravity models are non-unique with trade-offs between density contrasts, interface topographies, and layer thicknesses. Nonetheless, mantle upwarping beneath many large lunar and Martian craters is modeled from gravity data, and has been attributed to rapid uplift following impact (e.g., Wise and Yates, 1970; Neumann et al., 1996; Wieczorek and Phillips, 1998; Neumann et al., 2004; Mohit and Philipps, 2007).

Mantle topography has also been inferred beneath the large terrestrial Chicxulub impact crater. Seismic reflection profiles image crater-related crustal reflectivity that extends to the base of the crust and in places may be associated with faulting at the crust–mantle boundary (Morgan et al., 1997; Morgan and Warner, 1999). Initial modeling of a two-dimensional wide-angle seismic refraction profile collected in 1996 suggested that the Moho may be upwarped at the crater center; however, resolution analyses indicate that a model with no mantle upwarping will also adequately fit these data (Christeson et al., 2001). The timescale of mantle upwarping is inferred to be rapid based on the absence of upwarping and/or thinning of post-impact sediments in the center of the basin.

Here we analyze a more extensive dataset, using all seismic wide-angle data acquired in two separate experiments to produce a well-constrained three-dimensional map of Moho topography beneath the Chicxulub crater. These data show that the Moho is upwarped by ~1.5–2 km near the crater center, and depressed by ~0.5–1.0 km at a distance of ~30–55 km from the crater center. We also compare these results with new numerical models of Chicxulub crater formation. These results demonstrate that deformation from the Chicxulub impact extends to the base of the continental crust.

2. Location and seismic experiment

The 180–200 km diameter Chicxulub structure, located in the northwest Yucatan (Fig. 1), has been previously identified as the crater

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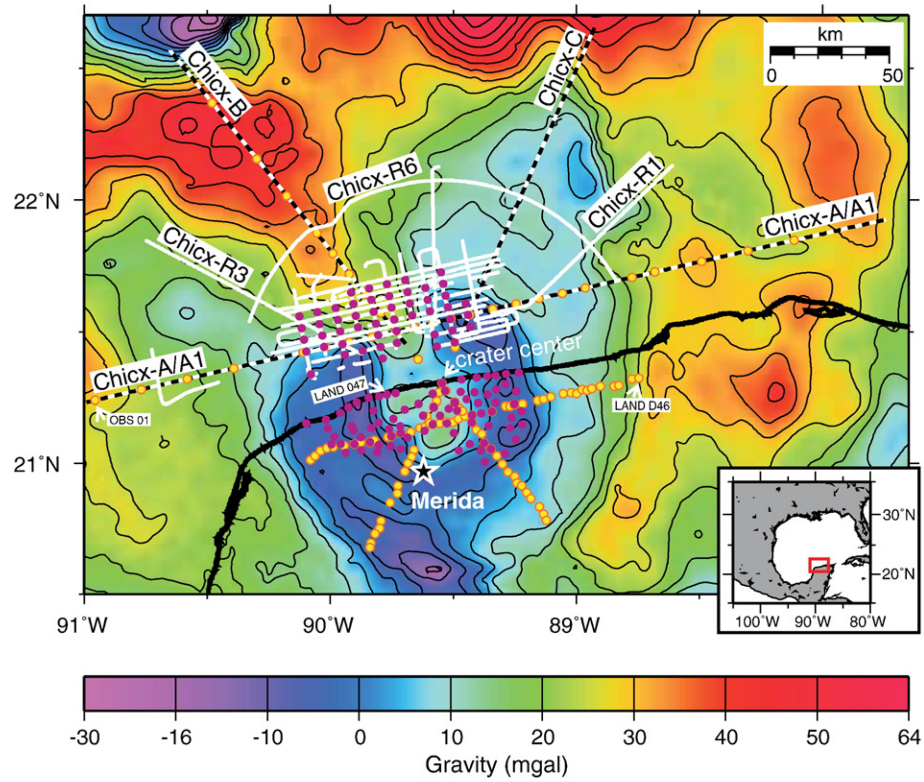

Fig. 1. Experiment location; background image is bouguer gravity anomaly map (gravity data courtesy of A. Hildebrand and M. Pilkington). Heavy black line marks the coastline. Black–white dashed and white solid lines indicate the locations of the 1996 and 2005 multichannel seismic profiles, respectively. Circles mark the ocean bottom and land seismometer locations used in our analysis from the 1996 (yellow) and 2005 (maroon) experiments; record sections of marked instruments are displayed in Fig. 2. Inset depicts the regional setting, with red rectangle outlining the region shown in the main location figure.

associated with the 65 Ma Cretaceous–Tertiary impact event (Hildebrand et al., 1991; Sharpton et al., 1992; Swisher et al., 1992). Other large terrestrial impact craters include the 2.02 Ga Vredefort crater in South Africa (250–300 km diameter) and the 1.85 Ga Sudbury crater in Canada (250–300 km diameter) (Grieve and Therriault, 2000). The Vredefort crater has been heavily eroded (Reimold and Gibson, 1996) and the Sudbury crater strongly deformed (Grieve and Therriault, 2000); in comparison the younger Chicxulub crater is relatively pristine owing to burial beneath ~1 km of carbonate rocks (Morgan et al., 1997) and the tectonically quiescent location of the impact site.

The 1996 Chicxulub seismic experiment (Fig. 1) consisted of ~650 km of marine seismic reflection profiles recorded on 34 ocean bottom and 91 land seismometers (Morgan et al., 1997). The 2005 seismic experiment (Fig. 1) acquired ~1500 km of marine seismic reflection profiles which were recorded on 28 ocean bottom and 87 land seismometers (Gulick et al., 2008). Representative record sections that display crustal refractions (*Pg*) and Moho reflections (*PmP*) are shown in Fig. 2. We utilized data from both field programs in our seismic analysis.

3. Methods

3.1. Crustal velocity structure

The goal of our seismic analysis is to map topography along the crust–mantle interface (Moho). However, inverting for the Moho interface requires that we first have a well-constrained three-dimensional crustal velocity structure that covers the entire region where instruments and shots are located that recorded *PmP* reflections. We therefore utilized the tomographic method described by Zelt and Barton (1998) to constrain the three-dimensional structure of the region using the first-arrival picks to create a velocity grid. Similar inversions were presented in previous studies (Morgan et al., 2002; Vermeesch and Morgan, 2008; Vermeesch et al., 2009) but these were high-resolution models focused on the crater center; our analysis differs in that shots and receivers from the entire 1996 and 2005 seismic experiment are included and hence the velocity tomogram covers a larger volume (365×248×40 km) but at a coarser resolution (1-km grid).

We picked all observed *Pg* first-arrival travel times for all seismometers at a 500-m spacing along each shot line. This resulted in a total of ~125,000 first-arrival picks. Our three-dimensional starting velocity model was constructed by linearly interpolating between two-dimensional velocity models previously obtained for profiles Chicx-A/A1 (Christeson et al., 2001), Chicx-B/F (Christeson et al., 2001), and Chicx-C (Brittan et al., 1999). The forward and inverse velocity grids were parameterized at 1.0 km. The tomographic inversion was carried out for ten iterations, and at each iteration three smoothing parameters were tested. The final preferred model was chosen as the iteration that produced the smoothest model with a chi-square value of 1.0 (i.e., the model fits the observed travel times within their estimated uncertainties which were set to 25 ms for source-receiver offsets <30 km, 50 ms for offsets 30–60 km, and 100 ms for offsets >60 km).

Four slices through the final velocity model are displayed in Fig. 3; plots show velocity anomaly with respect to average velocity for the entire region at each depth. Prominent features include a high-velocity anomaly near the crater center at ~5–10 km depth, a high-velocity region in the northwest, and a low-velocity region in the northeast. There is little ray coverage below 15–20 km depth, and thus these depths are not constrained by the tomographic inversion.

3.2. Moho interface

We solved for Moho interface depth using the method presented by Zelt et al. (2003). This technique uses one reflected phase (*PmP*) to invert for one interface (the Moho) with a fixed velocity model. We