Revisiting the Campo del Cielo, Argentina crater field: A new data point from a natural laboratory of multiple low velocity, oblique impacts

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Introduction: The energy of formation of very low angle impact craters in loess targets is not well-known. The Campo del Cielo, Argentina crater field (CdCcf) represents a natural laboratory of at least 22 low-angle impact craters formed in loess ~4000 years ago. Because of the uniformity of the loess and composition of the projectiles, as well as a limited range of impact velocities, calculation of energies of crater formation are simplified. Remaining variables are the masses of the impacting projectiles and the azimuths and angles of impact. Therefore, the CDCcf is an excellent location to obtain field data and relate these data to the impact process. Early work focused on the discovery and magnetic surveys of various craters in the CdCcf [1,2], but only 2 craters were excavated (1 in detail). Research to be carried out under the current grant will focus on examining more craters in the CdCcf and using theoretical modeling and hypervelocity impact experiments to understand the crater formation process. Here, we report on the results of the first year of current research. Two more possible craters were located in addition to 20 previously reported [1]. Extensive magnetic gradiometer and ground-penetrating radar (GPR) data were collected at two previously known sites (Craters 13 & 16). Crater 13 was trenched in three places and the meteorite that formed it was recovered. Data on Crater 13 follow.

Crater 13 magnetic gradient map: Figure 1 displays magnetic anomalies outlined using an Institut Dr. Foerster magnetic gradiometer. Gradients over a vertical interval of 60 cm were measured at ground level. Negative lobes appear deeper than positive ones. There is a positive/negative pair over the point where the meteorite was discovered, but the negative lobe is much closer to the location of the meteorite than is the positive one. This effect may be dictated by the relative strength of the negative lobe. Positive/negative pairs occur in other places in the crater where meteorites are not located. They parallel the apparent long axis of the crater; *i.e.*, the apparent azimuth of impact and consequent penetration path of the meteorite (compare Figures 1 & 2). We do not understand the cause of this effect, but speculate that there may be very finely divided NiFe grains liberally mixed into the infilling soil. Again, the stronger negative lobes are located closer to the entry path of the meteorite, which has been extrapolated from the structure of the crater.

Crater 13 structure immediately after impact: The structure of the original, pre-erosion crater is shown as Figure 2. Trenching revealed a lens of granular chunks of reddish clay that was assumed to outline deeper levels within the original crater. In this respect Crater 13 was similar to Crater 10 No structure was detected for about seven meters in front of the point where the Crater 13 meteorite eventually came to rest. This seems to be analogous to the situation at Crater 10, where the crater structure disappeared about 17 meters before the point where its meteorite came to rest.

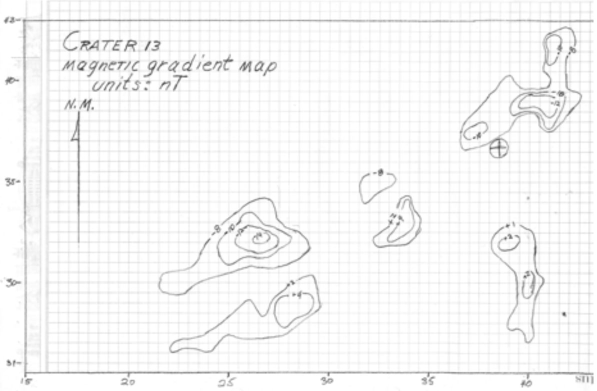

Figure 1. Magnetic gradient map of Crater 13. Units are in nanoTeslas (nT). ⊕ indicates the position of the meteorite.

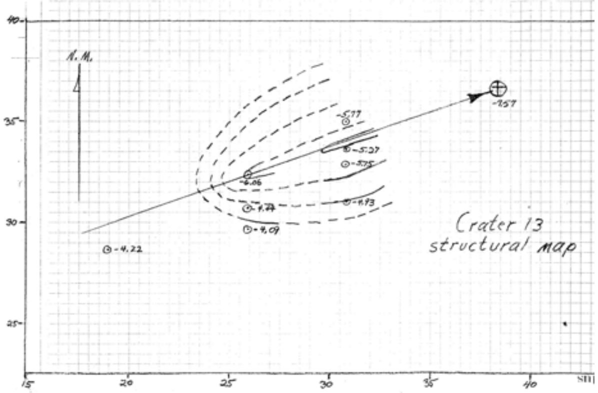

Figure 2. Structural map of Crater 13. Depths are in meters below the surrounding surface. ⊕ indicates the position of the meteorite.

Our interpretation of this would be the same in both cases: The impacting meteorite generated a shock wave in the target that excavated the crater. When the velocity of the impacting meteorite dropped below the speed of sound in the target material, the shock wave disappeared and the meteorite expended its remaining kinetic energy creating a penetration funnel that extends out of the shock-wave-excavated crater.

The inner walls of Crater 13 are not as well-defined as they were at Crater 10. The two most reliable points along the deepest parts of the crater/penetration funnel track are considered to be -6.06 m (labeled on Figure 2) and the bottom of the actual meteorite at -7.57 m. Based on these points, the angle of impact of the Crater 13 meteorite was about 8 degrees with the horizontal. Its azimuth of impact was N 70 E relative to north magnetic. Correcting for the current declination, the azimuth of impact was N 77.42 E relative to geographic north. Table 1 below compares data collected for Crater 13 to that of Crater 10 [2].

Table 1:

	Crater 10 [1,2]	Crater 13
$\text{Depth}_{\text{max}}$	4.6 m	6.0 m
Length	24 m	tbd
$\text{Diameter}_{\text{max}}$	16.4 m	tbd
Mass of Projectile	33400 – 36000 kg	14850 kg
Impact Angle	9° w/ horizontal	8° w/ horizontal
Azimuth of infall	N75.5°E (geog.)	N77.42°E (geog.)

GPR Survey: Ground penetrating radar (GPR) is a widely used geophysical tool for non-invasive exploration of the shallow subsurface [e.g., 3]. Penetration depth generally depends on the frequency of the radar and the properties of the subsurface materials. At Campo del Cielo, a 200 MHz antenna was used with the Geophysical Survey Systems, Inc. SIR-3000 controller. In the homogeneous loess, it was assumed that non-horizontal subsurface signals would be associated with original crater structure.

At Crater 13, GPR data were collected along parallel, north-south transects with 2 meter spacing and along several radial profiles. Transects along the boundaries of the survey grid show no reflections, but distinct subsurface structure is evident in transects near the outer rim of the expected crater location and within the expected crater. Radar data show what may be the original surface of the outer ejecta blanket close to the raised rim as well as the dipping inner crater wall. The radar structure reaches its deepest point at the crater center. Although the meteorite was not detected in field analysis of the data, further processing of the data could reveal its existence and guide future GPR exploration of the CdCcf.

Crater 13 meteorite recovery: After location by trenching and excavation, the meteorite was lifted out using a crane loaned by the Highway Department of Chaco Province (Figure 3). It was transported to Gancedo where it was weighed on a calibrated commercial scale and was then returned to the crater site. Its mass is 14,850 kg. There were no identifiable impact products in the sediments immediately surrounding the mass.

Future Work: The methodology followed for Craters 13 and 10 [1,2] will be duplicated for more craters. Field data will be applied to hypervelocity impact experiments and theoretical modeling in efforts to duplicate the observed crater parameters. Aerial and satellite remote sensing is currently being used in conjunction with ground truth data in an effort to locate more craters in the CdCcf.

Figure 3. Excavation of meteorite. The meteorite was located through analyses of magnetic gradiometer data, lifted with a crane, and weighed to be 14,850 kg. For scale, the width of the trench is ~2.5 m across. Reddish clay coating the iron octahedrite IA meteorite is a result of baked earth and subsequent weathering products of the iron and silicate inclusions. The cohesiveness of the loess allows for the construction of deep trenches (up to ~8 m shown here) and stairs.

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References: [1] Cassidy, W.A. and Renard, M.L. (1996) *Met. & Plan. Sci., 31*, 433-44. [2] Cassidy, W.A. and Wright, S.P. (2003) *Impact Cratering: Model. vs. Observ.*, #8004. [3] Ulriksen, C.P.F. (1982) *Applications of Impulse Radar to Civil Engineering*: Ph.D. Thesis, Sweden.