IMPLICATIONS OF THE CARANCAS METEORITE IMPACT. P. H. Schultz[1], R. S. Harris[1], G. Tancredi[2], J. Ishitsuka.[3] [1]Brown University, Department of Geological Sciences, 324 Brook Street, Providence, RI 02912-1846 (peter_schultz@brown.edu); [1]Dpto. Astronomía, Fac. Ciencias, Iguá 4225, 11400 Montevideo, Uruguay; [3]Instituto Geofísico del Perú, Lima, Perú

Introduction: The Carancas impact crater (just before noon on September 15, 2007) should not have happened. It is widely known that only iron meteorites are strong enough to survive atmospheric entry and produce small craters. The Carancas meteorite, however, is reported to be an H4/5 chondrite and formed a crater nearly 15m in diameter [1]. Not only did it did not disperse in the atmosphere before striking the surface, but the collision was witnessed by local inhabitants, detected by infrasound, and sampled soon after impact [1].

The Carancas Crater: The impact occurred in a dry stream (arroyo), but the crater excavation included an adjacent stream bank. Based on infrasound and witnesses, the trajectory was from near due east to west. The impact angle has been estimated to be 60° [1], whereas eyewitnesses and crater ejecta suggest a possibly lower angle ~45°. At the time of impact, the arroyo was dry, but water-saturated sands occur about 1.5m below the surface. A grassy topsoil (A horizon) extended irregularly over the steam bed from the stream bank. The stream embankment has a relief of about 1m with a fully developed soil sequence: tightly matted grassy surface on top of an organic clay layer (E horizon) over a layer containing an irregular calcium-carbonate layer (subsoil, horizon). The western crater rim is significantly higher than the eastern rim due to this local, pre-impact relief.

Soon after impact (based on videos 15 minutes after impact), several large spall blocks (~1-2 m, held together by the grassy uppermost soil) slid down an over-steep western crater. On the western rim, a few blocks remained hinged, either flipped over or steeply dipping. A fine, grey powder coated the western wall and rim. Within three months, most of the larger blocks (>20 cm) remained intact; however, many smaller fragments had disappeared due to trampling and disaggregation due to subsequent weathering. By contrast, the eastern wall initially had low relief and was covered by smaller (< 20 cm) blocks. On-site videos also reveal a tongue of water (low-speed) that covered the eastern wall and near-rim. Additionally there appeared to be a wedge-shaped gap (~30°) in blocky ejecta extending from the eastern rim, believed to be the uprange direction. This distribution is visible in images and videos soon after impact but has now been compromised by attempts to drain water from the crater floor in order to recover a suspected large meteorite mass (Fig. 1).

Ejecta around the crater rim exhibited the classic inverted stratigraphy, including individual blocks of different soil horizons flipped upside down [2]. A long ray (brown clays underlying the streambed with pieces of the overlying grass-matted soil) extended more than 300 m to the southwest [1]. Rays of the uppermost soil and clay blocks also extended to the west with a large ejecta (~20cm) clump of the uppermost grassy soil penetrating the roof of a shed ~150m the west. The abundance of ejecta to the north was also reduced. Meteoritic debris of varying sizes also was concentrated downrange to the west.

Discussion: Translated eyewitness accounts included the description of corkscrew pattern extending back up the fireball trail from the crater immediately after formation. This is consistent with a rotating mass. Reports also indicate that the object did not shed significant meteoritic debris during its final atmospheric entry. Consequently, it appears that a significant part of the meteorite was intact at impact. The maximum extent of the crater ejecta gives the impression of a NE-SW impact direction, but this impression was enhanced by pre-impact topography (the initial shock directed against the embankment) resulting in spallation of the grassy topsoil more orthogonal to the impact trajectory. Reduced ejecta to the north can be related to a slight change in the arroyo direction at the point of impact.

Local residents reported that water rapidly filled the crater and appeared to be boiling. Two processes were likely responsible. First, the compressed atmospheric air-cap in front of the body (and its trailing wake) accompanied the meteorite as it penetrated into the water-saturated sands at depth. In addition, clumps of clay falling into the water several months later were observed to froth and rapidly disaggregate. These two processes may have been responsible for local reports of water bubbling up from the floor soon after impact. While there would have been heat generated at impact, it is unlikely that this could have sustained bubbling an hour later.

The meteoritic mass, therefore, penetrated deeply while coupling its energy to the subsurface to produce surface spalls, inverted rim ejecta, injection of meteoritic debris between contrasting soil horizons [2], long crater rays [1], and excavation of horizons not exposed on the surface. The extended meteoritic debris downrange to the west is consistent with a reflected shock back into the projectile while retaining part of its initial momentum. The gap, the water emplaced uprange, shock effects [2], and peel-back of the arroyo embankment are all consistent with the mass penetrating to at least 3m below the surface. It was neither just a penetration nor atmospheric percussion crater. The altitude played only a small role since the object had already passed through most of the atmospheric column.

Excavation was clearly strength controlled. Impact scaling relations [using strength and gravity, density of the target (~1.5 g/cc), and impact velocity derived from the shock state of the target would suggest an object between 0.5m and 1m for the density of a stony meteorite. However, the effect of backpressure from the compressed atmosphere and the possible effect of more than one fragment (see below) could lead to a larger mass. Nevertheless, it remains smaller that other finds of massive stony meteorites that achieved their terminal velocity.

Implications: Models for atmospheric entry describe disruption followed by lateral dispersal by the interacting atmospheric mach cone, thereby producing a pancake-like assemblage of fragments [3,4]. Larger objects are able to produce crater fields such as Campo del Cielo [5], whereas smaller objects produce meteorite strewnfields after decelerating to terminal velocity. Stony masses exceeding $\sim10^{10}$ kg should survive to impact at speeds >14km/s, whereas a $\sim10^{8}$ kg will undergo catastrophic disruption at altitude [4]. It has been estimated that 65m is the smallest diameter stony meteorite that can reach the surface retaining 50% of its original entry speed with irons comprising only 5% of all the objects approaching the earth [6].

It appears that the standard pancake model may apply to relatively strong meteoritic bodies (irons) but needs to be modified for weaker objects, such as stony meteorites. Experimental [7,8] and theoretical [9] models provide a possible solution: weak or fragmented objects reshape during entry, thereby minimizing aerodynamic drag and stresses. In this case, the mach cone prevents fragments from escaping the mach cone, rather than spreading the fragments apart as in the pancake model. Experiments document this process using shadowgraphs [8] and demonstrate that the deceleration of even a cloud of debris passing through an atmosphere at hypervelocity can be significantly reduced resulting in minimal deceleration.

The impact shattered, distributed, and mixed a significant amount of meteoritic debris in the surrounding ejecta fines, not to mention the meteoritic cement that probably has developed below the floor. The survival of this amount of material is consistent with the derived impact speed [2] and raises a significant question for the surface of Mars. Current missions are discovering small (20 m) craters with blast zones, blocky rays, and near-rim ejecta. Prior studies have emphasized the important collective contribution of small-size meteorites [10] and impact melt to the surface [11,12]. Additionally many regions deflationary surfaces dating back 3 Ga. Impact melt, meteorites, and meteoritic dust from craters (distant or nearby Carancas size) all should have contributed to the surface.

The Carancas impact raises the possibility that there may be many more small craters produced by stony meteorites but unrecognized due to difficulty in identification. Large buried iron masses are easier to detect, whereas stony meteorites fully fragment at impact and become intimately mixed. Surviving fines are highly susceptible to chemical weathering and can become lost in sediments below a depression now described as a livestock or evaporation pond. Such a suggestion would be difficult (and exhausting) to test. The Carancas impact threw a hypervelocity curveball.

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Figure 1: Carancas impact crater from the southeast. Arrow indicates approximate trajectory (from E, dash-dot line). Solid lines trace arroyo bank; dotted lines, the grassy topsoil extending onto arroyo floor; and dashed line, region with gap in ejecta (uprange). Arrows show erosion of ejecta where water was drained from the floor. (Image by G. T.)

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