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Grazing Impacts Upon Earth's Surface: Towards an Understanding of the Rio Cuarto Crater Field

Martin Beech

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Abstract The origin of the Rio Cuarto crater field, Argentina has been widely debated since the early 1990s when it was first brought to public attention. In a binary on–off sense, however, the craters are either of a terrestrial origin or they formed via a large asteroid impact. While there are distinct arguments in favour of the former option being the correct interpretation, it is the latter possibility that is principally investigated here, and five distinct impact formation models are described. Of the impact scenarios it is found that the most workable model, although based upon a set of fine-tuned initial conditions, is that in which a large, 100–150-m initial diameter asteroid, entered Earth's atmosphere on a shallow angle path that resulted in temporary capture. In this specific situation a multiple-thousand kilometer long flight path enables the asteroid to survive atmospheric passage, without suffering significant fragmentation, and to impact the ground as a largely coherent mass. Although the odds against such an impact occurring are extremely small, the crater field may nonetheless be interpreted as having potentially formed via a very low-angle, smaller than 5° to the horizon, impact with a ground contact speed of order 5 km/s. Under this scenario, as originally suggested by Schultz and Lianza (Nature 355:234, 1992), the largest of the craters (crater A) in the Rio Cuarto structure was produced in the initial ground impact, and the additional, smaller craters are interpreted as being formed through the down-range transport of decapitated impactor material and crater A ejecta.

Keywords Meteorites · Rio Cuarto · Earth impacts · Planets and satellite · Surfaces

1 Introduction

Impact surface gardening and the impact alteration of surface morphology is a ubiquitous solar system process (Melosh 1989; Osinski and Pierrazo 2012). Indeed, all solid structures

M. Beech (✉)
Campion College, University of Regina, Regina, SK S4S 0A2, Canada
e-mail: Beechm@uregina.ca

from asteroids, cometary nuclei, satellites, through to dwarf and terrestrial planets, show evidence of ancient and ongoing cratering. It has long been known that the most probable angle with which an impactor will strike a target surface, for both gravitating and non-gravitating bodies, is at 45° to the local horizon (Pierrazo and Melosh 2000; Hughes 1993; Shoemaker 1962; for an historic perspective see Gilbert 1893). While collisions involving low impact angles (less than, say, 10°) to the horizon will be relatively rare, they will, none-the-less, occasionally occur. Indeed, the signature of such grazing impacts, in the form of distinctly elliptical crater profiles, is writ large upon the surfaces of the Moon, Mars and Venus (Schultz et al. 2012; Bottke et al. 2000; Schultz 1992), and to a lesser extent upon the Earth. Among the 175 presently catalogued terrestrial impact structures, only two have a distinct and measurable ellipticity that appears to be the result of a low-angle grazing impact. These structures are the various members of the Rio Cuarto crater field in Argentina, and the Matt Wilson crater in Australia (Kenkmann and Poelcha, 2008). The Rio Cuarto crater field has been described in detail by Schultz and Lianza (1992) and by Schultz et al. (2004) and it consists of at least ten elliptical craters, with length to width ratios varying from 2 to 4, spread predominantly over a 5 km wide by 30 km long range.

Although near universally included in catalogues describing Earth impact features, the Rio Cuarto craters remain controversial since an entirely terrestrial model has been hypothesized for their origin (see e.g., Bland et al. 2002 and the discussion below). Accordingly, we shall use the terms ‘crater field’ as well as ‘structures’ to describe the ground ‘features’ at Rio Cuarto in this article, but note that our primary interest is to determine how, if at all, such ‘features’ might be produced through the action of an extraterrestrial impactor. We do not directly discuss the dynamics behind the proposed aeolian, deflation-basin, model for the structures, and nor do we directly model the crater formation process itself. Rather our concern is with determining the initial conditions and atmospheric flight dynamics required of an asteroid in order that it might potentially produce the specific elongated structures (craters) observed at Rio Cuarto.

The influence of impact angle upon crater morphology has long been studied numerically via the application of hydrodynamic computer codes (Schultz and Lutz-Garihan 1982; Schultz and Gault 1990; and of recent note, see: Schultz et al. 2012; Miljkovic et al. 2013, and Elbeshausen and Wünnemann 2013) and through laboratory-based experimental means (Gault and Wedekind 1978; and of recent note, see: Davison et al. 2011; Giacomuzzo et al., 2007). The picture thus far developed indicates that crater plan profiles begin to become elliptical, that is, stretched-out in the down-range direction, once a certain material dependent threshold is reach (Gault and Wedekind 1978; Davison et al. 2011). For loosely compacted sand, for example, the threshold angle appears to be about 5°; for granite it is higher at about 30°. In support of these results, a detailed study of crater morphology conducted by Bottke et al. (2000) found that for the Moon, Mars and Venus the threshold angle for the onset of ellipticity is about 12°. In addition to increasing plan form ellipticity, as the grazing angle decreases so the crater depth decreases relative to that of a vertical impact and the crater profile becomes increasingly asymmetric with the deepest point being offset towards the up-range rim (Gault and Wedekind 1978; Davison et al. 2011). In addition, as the impact angle decreases below the threshold angle so more and more distal ejecta material is deposited down range—in extreme circumstances projectile decapitation can take place resulting in the potential for additional down range secondary cratering.

The probability that a specific impactor will enter the Earth’s atmosphere at an angle between φ and $\varphi + d\varphi$, where φ is measured from the vertical, is $dP = 2 \sin\varphi \cos\varphi \, d\varphi$ (Pierrazo and Melosh 2000; Shoemaker 1962). Upon integration, this probability function indicates that 50 % of all impacts will take place between $30 \leq \varphi^\circ \leq 60$, and that the most likely impact angle is 45°. Only 1 in 15 impacts will arrive with an impact angle $\phi < 15°$ to the horizon (here, $\phi = 90 - \varphi$); just 1 in 133 will arrive with $\phi < 5°$. An asteroid of diameter 100 m, traveling at 15 km/s, with an impact angle of $\varphi = 45°$, will characteristically produce a crater of diameter 1 km in a crystalline rock target (from—http://impact.ese.ic.ac.uk/ImpactEffects/), and such impacts will repeat on a timescale of order 5,000 years separation (Brown et al. 2002). Accordingly, only one distinctly oblique impact ($\phi < 15°$) might be expected to occur on Earth in every 75,000 year time interval—the expected time interval between $\phi < 5°$ impacts will be about nine times larger again at some 665,000 years. The time interval to accumulate an oblique impact from an even larger diameter asteroid will, naturally, be appreciably longer. While the occurrences of near-horizontal, small angle of impact events are going to be few and far between, the estimated age of the Rio Cuarto crater field is between 3 and 6 thousand years (Schultz et al. 2004—but also see the discussion below), making it both a relatively young geographical feature as well as potentially a structure of considerable interest with respect to the study of extreme asteroid interaction conditions with Earth's atmosphere.

In the analysis that follows an attempt is made to move towards a better understanding of the requirements of the impact formation scenario for the Rio Cuarto crater field. Specifically it is the atmospheric passage of the incoming asteroid that we look at. In this manner, a numerical code (described next) has been used to distinguish between several possible scenarios, each of which, in principle, is capable of accounting for the observed crater field. While our investigation is primarily directed towards an understanding of the Rio Cuarto structures, it additional elucidates the pre-impact conditions necessary for the formation of elongated craters, on Earth, in general.

2 The Numerical Model

With a number of additions, to be discussed here, the numerical procedure used in this study is that described in Beech (2013). The new adaptations to the code specifically concern the procedures for determining the drag coefficient Γ and heat transfer coefficient Λ. Rather than being assumed constant, these terms are now evaluated according to the characteristics of the oncoming airflow and atmospheric height. Using the Reynolds number *Re* as the regime defining characteristic, the drag coefficient is evaluated as

$$\Gamma = \frac{24}{\mathrm{Re}}\left[1 + \frac{3}{16}\mathrm{Re}\right], \quad \text{when Re} < 1 \tag{1a}$$

$$\Gamma = \frac{24}{\mathrm{Re}}\left[1 + 0.15\,\mathrm{Re}^{0.687}\right], \text{when } 1 < \mathrm{Re} < 10^3 \tag{1b}$$

$$\Gamma = 0.4, \text{when Re} > 10^3 \tag{1c}$$

where $Re = L\ V/\nu$, with L being the characteristic dimension of the asteroid (taken to be its diameter), V is the velocity of the asteroid through the atmosphere, and ν is the kinetic viscosity of the atmospheric gas. Equation (1a) is the Ossen approximation to the classic Stokes law formula, while (1b) is taken from Cliff et al. (1978). Equation (1c) is the limiting value for the high Reynolds number value to the drag coefficient for a sphere.

Following Melosh and Goldin (2008) the heat transfer coefficient is evaluated as

$$\Lambda = \frac{8}{\gamma}\left(\frac{Nu}{\text{Re Pr}}\right)\frac{1}{\Gamma} \quad (2)$$

where $\gamma = 1.4$ is the ratio of specific heats for air, Nu is the Nusselt number, and Pr is the Prandtl number. Melosh and Goldin (2008) provide formula for evaluating the Nusselt number (defined as the ratio of the convective to radiative heat transfer) in terms of the Mach number $M = V/c$, where V is the velocity of the asteroid and ($c = \sqrt{\gamma R T_{at}}$) is the atmospheric sound speed—with $R = 287$ J/K/kg being the gas constant for air, and T_{at} being the atmospheric temperature. The Prandtl number $\text{Pr} = C_P\,\mu/k = 0.72$ is the ratio of the kinetic viscosity to the thermal diffusivity—in evaluating Pr we take the specific heat of air to be $C_P = 1{,}005$ J/kg, the dynamic viscosity to be $\mu = 1.8 \times 10^{-5}$ Ns/m^2, and the thermal conductivity to be $k = 0.025$ W/mK. In line with expectation, the formalism for Λ results in the heat transfer coefficient decreasing with decreasing altitude and with increasing velocity.

The atmospheric density variation with height used in this study has additionally been updated and is now formulated via a least squares polynomial fit to an *NRLMISE-00* (Picone et al. 2002) atmosphere model evaluated at 5 km intervals over the range 0–400 km altitude. The *NRLMISE-00* model is also used to evaluate the atmospheric sound speed via a series of least square polynomial equations in height constructed to describe the variation of atmospheric temperature T_{at}.

As in our previous study the equations to be solved (Appendix I of Beech 2013) are those following the height, ground path, velocity and mass of the incoming asteroid allowing for the curvature of an assumed perfectly spherical Earth. The latter ability better enables the study of conditions under which an asteroid traverses Earth's atmosphere under very shallow angles of entry. Additionally we follow the stagnation pressure $P_S = \rho_{at}\,V^2$, where ρ_{at} is the atmospheric density and V is the asteroid's velocity, experienced across the leading face of the incoming asteroid as a function of atmospheric height. This quantity is then used to determine the conditions under which the asteroid might be expected to start breaking apart: namely, once $P_S > \sigma$, where σ is the unconfined crushing strength of the impactor material—this strength limit is discussed more fully in the next section. For the moment, however, it is clear that a diverse range of outcomes are possible once an asteroid begins to break apart in the atmosphere. At one extreme, a rapid cascade to smaller and smaller fragments might be produced with a catastrophic airburst explosion eventually taking place—this would be something similar to that exhibited by the 1908 Tunguska (see, e.g. Chyba et al. 1993; Boslough and Crawford 2008) and 2013 Chelyabinsk events (Borovicka et al. 2013; Popova et al. 2013). At the other extreme we might envisage the asteroid simply breaking into two, equal mass, components. Equally, the possibility of no fragmentation at all, in spite of general expectations, can not a priori be ruled out. The 2007 Carancas meteorite fall and cratering event in Bolivia (Borovika and Spurny 2008) is one such example of an event where fragmentation might have been expected, but apparently no catastrophic break-up took place (Tancredi et al. 2009). While standard theory and the (still) limited observational data must certainly guide our general expectations concerning fragmentation, this does not mean that the entirely unexpected or highly improbable result cannot occur.

If the asteroid break-up condition imposed within our numerical simulations is exceeded then the lateral spread of the individual fragments, due to bow shock interactions, is determined according to the procedure outlined by Passey and Melosh (1980). While the lateral spread of fragments is determined analytically, and parameterized according to the break-up height, the size and density of the fragments, the velocity, angle to the horizon and ablative mass loss of the fragments are determined numerically and followed to ground impact. With ground impact, the resultant crater characteristics are determined according to equation (21*) presented in Collins et al. (2005). The key input parameters being the impact velocity, the angle of impact, the size of the impactor and the density of the target and impactor materials.

3 Model Parameters

Numerical models are only as good as the uncertainties (or certainties) within their basic equations and input parameters. While we have confidence in the numerical procedure for describing the dynamical interaction of an asteroid with Earth's atmosphere, the key uncertainty is that of the physical make-up of the asteroid itself. Specifically it is the conditions for fragmentation onset, along with the number and size of the fragments produced during fragmentation that are poorly constrained at the present time. The processes at play are clearly stochastic and are largely dictated to by the unique collisional history of each individual asteroid. Two numerical approaches have been adopted to account for fragmentation effects: one, often called the pancake model, treats the entire object as an incompressible fluid and allows the profile to change shape in response to the differential atmospheric pressure across the objects profile (Bland and Artemieva 2003; Hills and Goda 1993; Zahnle 1992; Herrick and Philips 1994; Boslough and Crawford 2008), the second approach assumes some power law variation for the number versus size distribution of fragments and then follows each fragment to a terminal ground or ablation destruction end phase. The latter model can be used to investigate the arrangement, that is, sizes and relative locations, of an extended crater field, while the former model brings the entire, extended and deformed body to a single ground impact or airburst explosion. As indicated in the previous section we adopt the approach of assuming some form of specific fragmentation mode (to be described in the next section) and then follow individual fragments to their ground impact locations.

The onset of break-up height is typically determined according to the point at which the stagnation pressure P_S on the leading hemisphere of the impactor becomes larger than the crushing strength σ of the impactor material: as before, this is written as $P_S > \sigma$. Key to modeling the fragmentation process is the expression of σ appropriate to the specific object undergoing fragmentation. Atmospheric break-up, for example, occurred once $P_S \sim 5$ MPa in the case of the 2013 Chelyabinsk (LL4 chondrite) meteorite fall (Borovicka et al. 2013; Popova et al. 2013; Brown et al. 2013) indicating that it was a highly fractured object. In contrast, the apparent non-fragmentation during the (H4-5 ordinary chondrite) 2007 Carancas meteorite fall and cratering event implies a parent-body crushing strength possibly as high as 40 MPa (Borovika and Spurny 2008). A comprehensive study and review by Popova et al. (2011) of the break-up conditions for meter-sized objects producing well-documented meteorite falls indicates typically low bulk strengths of between 0.1 and 1 MPa at first break-up, and strengths of order 1–10 MPa for secondary break-up events. These results indicate that meter-sized objects are typically highly fractured prior to encountering the Earth's atmosphere and that in some cases they are hardly more than weakly bound rubble piles.

How the crushing strength of a typical asteroid body varies with size is not known. The usual response to this lack of direct knowledge is to assume a fracture-size distribution corresponding to Weibull statistics such that for an object of mass m, $\sigma = \sigma_0(m_0/m)^{\alpha}$, where σ_0 and m_0 are some measured sample values, and α varies according to the material concerned. This form of relationship implicitly (unless $\alpha = 0$) assumes that larger, that is more massive, objects have lower crushing strengths than smaller-sized objects—in other words, bigger objects can support larger fractures within their interiors than smaller similar composition objects and are accordingly less strong (Svetsov et al. 1995). This specific rule may or may not be universally true for the multiple-tens to a few hundreds of meter sized asteroids, and up to a point there is no specific set of observations to rule out the possibility that objects in this size range are much better able to resist atmospheric break-up than their smaller-sized siblings.

In the analysis to follow a range of conditions for asteroid fragmentation during atmospheric passage will be adopted, and, rather than impose a typical rule or formula for the onset of break-up, our analysis will be tied to a set of specific models that might conceivably explain the broad features of the Rio Cuarto crater field.

4 The Rio Cuarto Structure

The cratering and impact history of the Pampean plane in Argentina is complex and not fully understood at the present time (Schultz et al. 2004, 2006; Bland et al. 2002) although eight distinct impact horizons have been identified over the extended region, with the oldest impacts occurring some 5–10 million years ago in the Late Miocene. This being said, Schultz et al. (2004) find from the radiometric study of the impact melt breccias's located within the Rio Cuarto region that at least two impacts have occurred in the region. The craters of interest in this study relate to an impact located some 6 ± 2 thousand years in the past. The second impact melt breccia horizon is dated to a much earlier event occurring 114 ± 26 thousand years ago. A third even older impact horizon has additionally been identified, occurring 570 ± 100 thousand years ago, by Bland et al. (2002). The radiometric age of the first impact melt breccia horizon is consistent with the geological context age of the Rio Cuarto craters, as deduced by Schultz et al. (1994), as being some 4–10 thousand years. Masse et al. (2009) have further argued that the potential energy associated with the formation of the Rio Curato crater field could have exceeded many tens to even thousands of megatons of TNT equivalent energy, and accordingly devastated an extensive region of some 50,000 km^2. Interestingly, as well, Masse and co-workers note that it is potentially possible to temporally link the 'world fire' and 'new creations' myths and motifs of several South American cultural groups to eye-witness accounts of the formative Rio Cuarto impact (and possibly to that of the Campo del Cielo iron meteorite fall, also estimated to have occurred $\sim$4,000 years ago: see, e.g., Wright et al. 2006). The highly elongated structures that constitute the Rio Cuarto crater field were first noticed, in recent times, by Ruben Lianza in 1990, and they constitute distinctive shallow, rimmed features located within the loessoid deposits that distinguish the Pampas of Argentina. Schultz and Lianza (1992), Schultz et al. (1994) and Schultz et al. (2004) find that the structures have undergone both aeolian and agricultural reworking, but argue that they are structurally distinct from the numerous wind-formed deflation basins that are additionally scattered across the Pampean plane. This result, we note, is in direct contrast to the conclusions drawn by Bland et al. (2001, 2002). Indeed, Cione et al. (2002) have argued that the Rio Cuarto structures have an entirely terrestrial origin, and that they, in fact, form part of an extensive network of many hundreds of geoform relics aligned according to the preferential wind directions that have existed during past geological epochs. Schultz (private communication), however, counters these findings by noting that the craters do have a distinct morphology, and that they follow a linear orientation pattern rather than that of the curved or arching alignments displayed by the geoform depressions. Bland et al. (2002) further argue, however, that the Rio Cuarto structures have a comparable age, of order 480,000 years, to impact glass collected some 800 km away in Necochea. This, they suggest, indicates the existence of an extensive tektite (impact glass) strewn field across a vast swath of the Pampean plane. Accordingly, the impact glass found within the Rio Cuarto craters is attributed by Bland et al. (2002) to the distal debris associated with a single 500-m diameter asteroid impact taking place some 0.5 million years ago. Model simulations further indicate that the formative impact would produce a crater some 5-km in diameter. As of the present time, however, no candidate for the required parent crater has been identified. The observations presented by Bland et al. (2002) along with those of Cione et al. (2002) provide a potentially powerful counterargument to the impact origin for the Rio Cuarto structures, but it would appear that the ground-work data relating to comparative formation ages of the specific craters as well as the various impact glass horizons is still largely wanting—or at least requiring consensus. Likewise there is no complete understanding of the formation histories relating to the near-by aeolian depressions, and nor are the transport mechanisms for surface-exposed materials fully understood. Accordingly, while interpretations for the origins of the elliptical structures within the greater Pampean plane certainly vary, and while a terrestrial origin is entirely possible, we would argue that an extraterrestrial origin has not, as yet, been definitively ruled out by any of the available data. What has been revealed to date is that the Pampean plane has suffered a long and complex impact alteration history. This situation is borne out, in fact, by the data relating to the various small meteorites found within the region of the Rio Cuarto structures (specifically within craters E and D) by Schultz and Lianza (1992), Bland et al. (2002). Some 5 ordinary chondrite (H4-5) meteorites and one achondrite meteorite have so far been collected from the region of the Rio Cuarto structures. Bland et al. (2002) report terrestrial residency ages of 36,000 years for a single chondrite found in crater D, and >52,000 years for an achondrite found in crater E. Later analysis of the achondrite (now official designated Rio Cuarto 001) by Levine et al. (2008) deduced a terrestrial residency age of 410,000 years. Concentrations of cosmogenic elements further indicate that this particular meteorite was derived from a pre-impact body no larger than about 1 m across. For an achondrite the deduced residency time of Rio Cuarto 001 is highly unusual, and if correct, indicates a much older terrestrial lifetime than would otherwise be expected for the environment in which it was found (i.e., a predominantly wet, agricultural environment). Likewise, Serefiddin et al. (2005) have studied the cosmic ray exposure (CRE) ages of three H-chondrites collected at the Rio Cuarto location. The results of this study indicate CRE ages of 3.5, 8.0 and 12.2 million years for the samples labeled RC2, RC3 and RC1 respectively. Radionuclide analysis further indicates that these three meteorites are not paired and that they are apparently derived from 3 distinct falls associate with precursor bodies that would have been no larger than a few meters across. It appears, therefore, that the various meteorite samples collected in the Rio Cuarto region are not directly linked to a single impact or crater forming event. Indeed, the variety of meteorite finds indicates a long, widespread and complex history of meteorite falls across the Pampean plane—up to December 1999, 62 distinct meteorite falls and finds, covering nearly all petrographic types, are recognized from across Argentina (Grady 2000). In addition to having a rich meteorite exposure history, it is evident that surface transportation, lag deposit accumulation and impact horizon mixing processes have all been at play in the Rio Cuarto region for many thousands of years. Cione et al. (2002), for example, indicate that they found numerous samples of small metamorphic rock fragments within the Rio Cuarto structures that appeared to have undergone fluvial transport from a region located some 15 km away.

The meteorite data, as it presently exists, appears to neither strongly support nor specifically negate an impact origin of the Rio Cuarto structures. Indeed, it would be surprising if there were no meteorite strewn field produced as a result of the crater formation process, but it would additionally appear that if such a strewn field exists it has not, as of yet, been clearly identified within the ground surveys so far conducted. With all of the above caveats in place, in what follows next it is our intention to investigate how the Rio Cuarto structures might have been produced by an asteroid impact, although we additionally acknowledge that alternative terrestrial formation scenarios are entirely possible.

In order to produce the Rio Cuarto crater field the impactor(s) must have been sufficiently large to produce and disperse melt breccias and debris over an extended region of at least 100 km in the downrange direction (Schultz et al. 2004). There are three principle craters, however, and numerous (at least 8) smaller structures that are distributed over a region of some 35 km in extent—it is these features upon which we focus our attention (see Fig. 1). Using the labeling of Schultz and Lianza (1992), crater A is the largest structure and measures 4.5 × 1.1 km rim to rim. Situated some 15 km to the southwest of A are two similar sized craters E and D (with dimensions of ∼3.5 × 0.7 km) that run parallel to each other, with their central axis lines separated by some 2 km. A third set of three parallel craters G, F, and H (having dimensions ∼1 × 0.1–0.3 km) are additionally located 7.5 km to the southwest of craters E and D. Crater F falls along the central axis line extended through crater A, while its neighbours are displaced by ∼0.5 km on either side of the axis line. Crater B, having dimensions of ∼1.5 × ∼0.5 km, is located 9 km southwest of crater A and it additionally falls along the central axis line extended through crater A. A small ∼1.0 × ∼0.2 km crater, crater C, is located about 1 km downrange of crater B in line with the central axis of crater E but displaced by ∼1 km from the central line extended through crater A. Three smaller elongated craters (I, J, and K) are situated 5 km downrange of craters G, F, and H with perpendicular displacements of about 5 km from the extended central axis line of crater A.

In principle the distribution of craters within the Rio Cuarto field is not overly complex. There is an apparent axis of symmetry which runs through the centers of craters A, B, and F, and midway between craters E and D. Indeed, it is the origin of these specific craters that seems to be the most important features to reproduce. Once these major structures are understood then the remaining smaller craters can be thought of as natural secondary phenomenon. While we are not concerned with the modeling of the actual crater producing process in this article, previous studies (Schultz and Lianza 1992; Bland et al. 2002) have argued that an impactor of order 100–150 m across would be required to produce crater A—stony asteroids with these dimensions will have characteristic masses between 1.5 and 5.5×10^9 kg. Craters E and D, both being somewhat smaller than crater A, will presumably require impactors having a characteristic size of order 75–100 m across for their production. In the analysis that follows these impactor sizes are taken to be representative rather than definitive.

5 Formation Scenarios

While it might at first appear that a large number of interpretations for the Rio Cuarto structures are possible, there is actually a reassuringly small list of scenarios under which the craters could have been produced through the direct impact of an extraterrestrial body or bodies. That the angle of impact must be small is clear from the elliptical crater

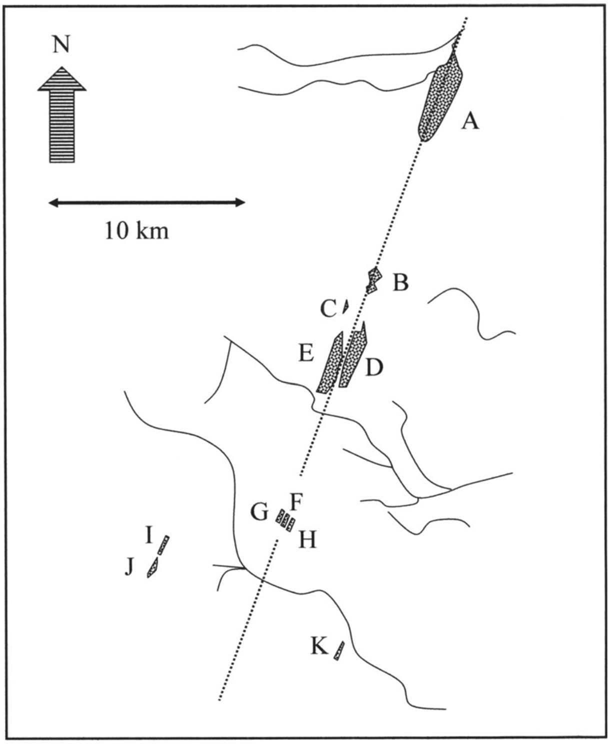

Fig. 1 Schematic map of the Rio Cuarto crater field showing the relative locations of craters A through to K. The *dotted line* is the extended symmetry axis line drawn through crater A. Image based upon figure 1 of Schultz and Lianza (1992). See also Sosa et al. (1995) for additional descriptions of the crater field

morphology, but after this constraint, the resulting crater distribution could be explained according to the following five scenarios:

(1) A single body impact (Schultz and Lianza 1992). In this scenario a large 100–150 m diameter asteroid survives atmospheric passage without significant fragmentation until impact occurs. In the process of producing crater A the impactor is decapitated and sends downrange two significant pieces of original body-material, which produce craters E and D. Smaller fragments of the original impactor also continue down range to produce the remaining smaller craters. In this scenario the direction of motion is implicitly taken as being from the northeast to southwest.

(2) The atmospheric fragmentation of a large 100–150 m diameter asteroid. Under this scenario a small number of large fragments (2 or 3) are formed prior to ground impact and these produce the primary impact structures A, E and D. Numerous smaller mass fragments are invoked in the production of craters, B, C, I, J and K. In this scenario the direction of motion is from the southwest to northeast (the reverse of scenario 1), and the down range spread in the crater locations is the result of differential area-to-mass ratio sorting.

(3) The impact of a double asteroid. This scenario envisions the entry, in rapid succession, of the two components both of order 100–150 m in diameter. The one component produces crater A with secondary craters B and C, while the other

secondary companion fragments during atmospheric passage to produce craters E and D, with secondary downrange craters F, G and H. Under this scenario the original direction of motion could be either from the northeast to the southwest or visa versa.

(4) The impact of an asteroid swarm. In this scenario each crater is produced by a single impactor with no downrange secondary craters being formed. Under this scenario the motion of the impactors could be either from the southwest towards the northeast or the other way around; just the mass and entry times of the impactors need to be adjusted in order to accommodate the specific downrange/up-range crater size distribution. Additionally, atmospheric fragmentation may, or may not be required to explain the lateral shift in the parallel crater configurations.

(5) The accumulation of multiple grazing impact events in the same small region over an extended period of time.

In principle any one of the scenarios described above could account for the impact origin of the Rio Cuarto crater field, but, of course, some of the scenarios (all of which are going to be rare events) have a much lower probability of actually occurring. Scenario (5), for example, can be reasonably dismissed straight away. At issue here is not that multiple impacts in the same region are impossible, indeed, the ages associated with the various meteorites and the impact glass breccia's in the Rio Cuarto region indicate that multiple impacts must have occurred in the greater region during the past half-million years. Rather, and in addition to there being no strong ground evidence to indicate that the Rio Cuarto craters themselves formed at different times, the odds of separate grazing impacts occurring, at the same geographical location, over a 100,000 year interval of time are astronomically small. Indeed, the global impact rate for 100–150 m diameter asteroids is of order one per 20,000 years (using Brown et al. 2002). As discussed earlier only 1 impact in 15 is likely to have an angle of impact smaller than 15° to the horizon, which implies a grazing-impact occurrence rate for asteroids having sizes in the range of interest are of order one per 300,000 years. This impact occurrence rate must be further modified to account for the area of interest surrounding the Rio Cuarto crater field—a region, say, some 50×50 km. Comparing this area to the total area of Earth's surface, an additional factor of 2×10^5 for repeat impacts in the same small geographical location is introduced. All in all, scenario (5) might only be likely on a timescale ten times longer than the Earth is actually old. Likewise, we would attach a very low probability to scenario (4) as being the correct explanation for the Rio Cuarto crater field. At issue in this scenario is not that pre-Earth-encounter breakup is unlikely, but it is unlikely that the Earth will encounter an asteroid swarm before its constituent fragments had dispersed appreciably around the parent objects orbit. Certainly asteroid families, indicative of disruptive collisions, have been identified in the main belt region, but these objects will certainly not feed coherently into the near-Earth asteroid population. Bottke et al. (1997) have examined the conditions leading to the tidal disruption of a near-Earth asteroid in the Earth-Moon region of the solar system, with the specific intent of explaining crater chains, and they find that only 1 crater chain is likely to form on Earth per 360 billion year time interval. Accordingly, the odds of the Rio Cuarto crater field being the result of the Earth encountering a newly disrupted, asteroid debris swarm, in the last 6,000 years is of order 1 in 60 million.

One aspect of scenario (4) that is more compelling is the way in which the range between craters can be explained entirely in terms of initial mass. Figure 2 illustrates the results from a series of calculations in which it is envisioned that a swarm of meteoroids encounters the Earth's atmosphere at the same time, with the same initial velocity of

12 km/s and with the same entry angle of 14° to the horizon. In this situation the direction of motion would be from the southeast towards the northwest and the range separation is a consequence of the different area-to-mass ratios presented by the various swarm components. From Fig. 2 it is seen that if crater A is produced by a 150-m diameter impactor (mass $\approx 6 \times 10^9$ kg) then craters E and D, at a downrange distance of 10 km, would be produced by impactors of mass $\sim 5 \times 10^7$ kg (diameter $\sim$30 m). Likewise, craters F, G and H, at a down range distance of 20 km from A, would be produced by impactors having masses of order 5×10^6 kg (diameter $\sim$15 m). For the swarm being simulated, there is a range of fragmentation onset heights (the model calculations assume a two values of $\sigma = 10$ and 50 MPa) varying from about 10–20 km in altitude for the largest mass components, down to no fragmentation (for $\sigma = 50$ Mpa) for masses smaller than $\sim 5 \times 10^6$ kg. Although the fragmentation height is calculated we assume that the body carries onward towards the ground as a largely coherent object—this allows us to estimate the final impact velocity and impact angle. The impact velocity varies across the swarm mass range, with the largest mass components having impact velocities of order 8–10 km/s; the smaller mass components, in contrast, strike the ground at speeds of order 3–6 km/s. Since the smallest mass members of our putative swarm will be decelerated more effectively than their larger companions during atmospheric passage, so their forward motion is greatly reduced and the angle with which they impact the ground increases towards the vertical. In the simulation considered here the impact angle is always smaller than 14° to the horizon, but the more massive swarm members have progressively smaller angles of impact, down to a value of order 5°.

Scenario (3) for the origin of the Rio Cuarto crater field is predicated upon the impact being a binary pair. Based upon the number of double-craters preserved upon the surfaces of the terrestrial planets and the Moon, Bottke and Melosh (1996) estimate that the near-Earth asteroid binary fraction is of order 15 %. Given, therefore, that of order 1 NEA in 7 is binary or multiple in nature, so the odds of the Rio Cuarto crater field being produced by the Earth encountering such an impactor in the last 6,000 years is of order 1 in 350. To explain the observed crater distribution, one component of the binary impactor would need to survive atmospheric passage essentially intact until ground impact, thereupon producing crater A and its (assumed) subsidiaries B and C. The second component, however, while assumed as being similar in size to its companion, would need to undergo atmospheric fragment at a height of order 20 km in order to reproduce the observed 2 km lateral spread observed between craters E and D. The fragmentation height for the secondary component is based upon a series of simulations (see Fig. 3) in which a 150-m diameter stony impactor enters the atmosphere with an initial speed of either 11 or 15 km/s, and where it is assumed that two equal-mass components are produced when the ram pressure exceeds 20 MPa.

It would appear from the numerical simulations resulting in the production of Fig. 3 that the crushing strength of the secondary impactor needed to produce craters E and D need not be abnormally high in order to account for their ground-measured total cross-range displacement of $\sim$2 km. For a crushing strength of 10 MPa the cross-range spread would be on the small side ($\Delta \sim$ 1.5 km), while for 35 MPa, the cross-range spread is slightly too large ($\Delta \sim$ 2.5 km). For the primary impactor to survive atmospheric passage without fragmenting, however, would require an abnormally high crushing strength—a value between 100 and 200 MPa. Indeed, here it makes sense to invoke the development of some form of near-fully disaggregated, pancake-model-like structure (Bland and Artemieva 2003; Hills and Goda 1993; Zahnle 1992). This situation is in contrast to the fate of the secondary which must first 'split' into two large, near-equal mass (size) fragments. While these two components proceed onwards to produce craters E and D, it is likely they too,

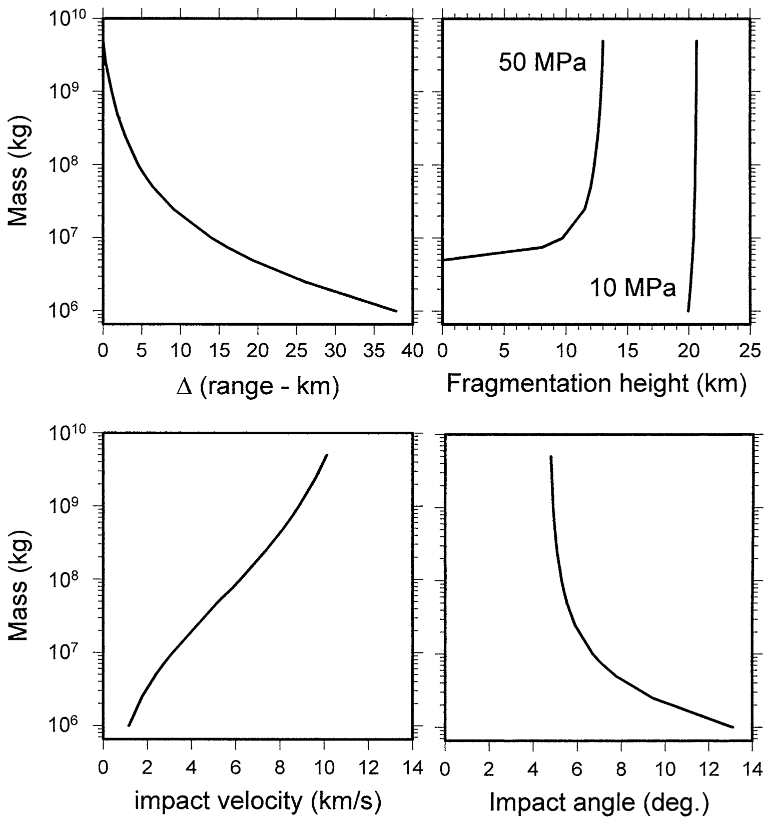

Fig. 2 (*top left*) Range separation (Δ km), (*top right*) fragmentation height (km) (for assumed values of $\sigma = 50$ and 10 MPa), (*lower left*) impact velocity (km/s) and (*lower right*) impact angle (degrees to the horizon) for initial masses in the range 10^6–5×10^9 kg. In each case the initial velocity is 12 km/s and the initial entry angle is 14° to the horizon

upon impact, will have an extended pancake-model-like structure. The origin of craters B and C, and F through K may be accounted for in scenario (3), as either individual smaller fragmentation components, or secondary, down-range impacts produced from 'splash' or projectile decapitation ejecta derived from the formation of craters A and E and D.

Scenario (2) might be considered the canonical model, with the crater distribution mapping out the large-impactor component of an extensive meteorite strewn-field. In marked contrast to scenarios (3), (4) and (5), however, this scenario specifically requires that the motion of the original impactor is from the southwest towards the northeast. This requirement follows since it is differential area-to-mass ratio sorting that will determine the range of crater displacements; smallest craters (I, J and K) appearing up-range, and largest craters (A, E and D) downrange. Table 1 summarizes the results from a model simulation in which three key fragmentation events are invoked to produce four crater groups. In this manner, crater A is formed by a 150-m diameter (main mass) impactor, while craters D and E are produced by the break-off of a fragment having an initial diameter of 20 m at a height of 26.1 km altitude when the ram pressure is of order 3.1 MPa. Craters F, G, and H are the result of a fragment, with an initial diameter of about 14-m, breaking-off the main

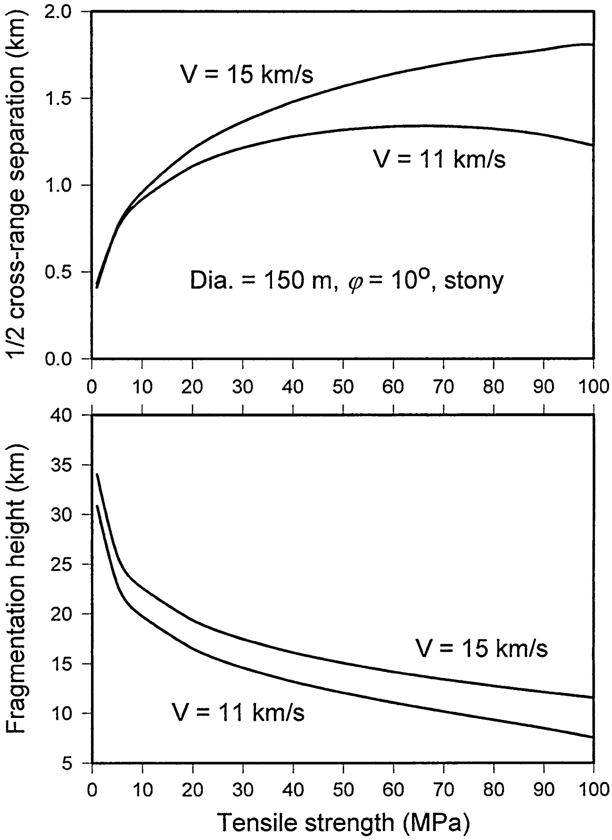

Fig. 3 (*top*) The ½ cross-range separation [based upon equation (26) of Passey and Melosh (1980)] versus material strength. (*bottom*) Fragmentation height versus material strength. The calculations assume a material density of 3,400 kg/m^3, an initial diameter of 150 m, and an initial entrance angle of 10° to the horizon. Break-up occurs once the ram pressure exceeds the specified material crushing strength, and it is assumed at that time two equal mass (equal size) components are produced. Two initial velocity values of 11 km/s and 15 km/s have been adopted in the calculations. For the former initial speed, the fragments have impact speeds of ~9 km/s and impact angles of ~7° to the horizon. For the latter adopted initial velocity, the impact speeds are ~12 km/s and the impact angles are ~5° to the horizon

mass at an altitude of 31.8 km when the ram pressure is of order 1.0 MPa. And, finally, craters I, J and K are produced through the breaking-off of a fragment, of initial diameter 13-m, at an altitude of 15 km when the ram pressure is some 25 MPa. In terms of formation time, crater A is produced first followed, some 11 s later, by the production of craters D and E. Craters F, G and H form 5.5 s after craters D and E, and finally, some 20 s after the production of crater A, the up-range craters I, J and K are produced.

The model summarized in Table 1 is not intended to provide a unique description to the Rio Cuarto crater field; rather it is presented as an example simulation that begins to describe the specifics of a fragmentation model capable of explaining the gross-features of the Rio Cuarto crater field. The simulation essentially invokes the successive production of minor constituent fragments from the main, crater A producing, mass, with the fragmentation masses and fragmentation heights (set according to the ram pressure) being adjusted

Table 1 Summary of a scenario (2) fragmentation model simulation

Crater(s)	$M_{initial}$ (kg)	Range (km)	Spread (km)	$h_{fragment}$ (km)	M_{impact} (kg)	V_{impact} (km/s)	θ_{impact} (deg.)	$P_{fragment}$ (MPa)
A	6.0×10^9	–	–	–	6.0×10^9	10.2	4.8	–
D, E	1.4×10^7	15	1.5	26.1	6.9×10^6	2.7	7.2	3.1
F, G, H	5.0×10^6	25	1.0	31.8	2.5×10^6	1.8	9.4	1.0
I, J, K	3.5×10^6	33	3.5	15.1	1.1×10^6	1.2	12.4	25.0

Column 1 indicates the specific Rio Cuarto crater group being described. Column 2 is the initial mass of the progenitor fragment—crater A is produced by the main mass). Columns 3 and 4 indicate the relative downrange location, as measured from crater A, and the total lateral spread about the symmetry line projected through crater A. Column 5 indicates the height at which the various fragments are released into independent flight. Columns 6, 7 and 8 describe the mass, velocity and ground angle of the impacting fragments. Column 9 is complementary to column 5 and indicates the ram pressure at the fragment release heights so as to produced the observed crater range and lateral displacements. We note here that we were unable to fully account for the 10-km lateral displacement observed between craters I, J, and K—even for very low altitude fragmentation events, when the lateral displacement effect is at its optimum efficiency, the best results we could obtain gave a maximum separation of 3.5 km (just 1/3rd of the required value). In addition, we also note that after each specific fragment has been produced we do not of necessity require that it remains coherent during its final descent to the ground (although that is the model adopted)—indeed, the specific fragments, once displaced and set in motion, could undergo radial-spreading as invoked in the pancake model.

In terms of basic expectation, scenarios (1) and (2) are the most likely events to occur: the odds of a single, 150-m diameter impactor producing a terrestrial crater field within the past 6,000 years being of order 1 in 3. In terms of standard theory, however, in which atmospheric fragmentation is taken as being almost, if not absolutely, inevitable, then scenario (2) would normally be favored over scenario (1) as the best model choice. Scenario (1), however, is far from ruled out if one allows for only a moderate increase in the typical range of crushing strengths adopted for asteroidal bodies. To illustrate this we have performed a series of numerical simulations for 100 and 150-m diameter asteroids encountering Earth's atmosphere at their lowest allowed velocity of 11.2 km/s. For these least initial velocity impactors we have also adjusted the horizon impact angle to be as close as possible to the smallest allowed value resulting in a ground impact. In this manner we are deliberately setting-up (or fine-tuning) the situation in which the impactors have the slowest possible initial velocity and the longest possible atmospheric flight path—a situation that will result in the longest atmospheric deceleration time and lowest peak ram pressure.

It would appear from the calculations leading to Fig. 4 that scenario (1) is potentially viable, albeit as a highly rare event, and that the Rio Cuarto craters are possibly the result of a single impactor that was captured into temporary Earth orbit. Our simulations indicate, for example, that for an initial horizon angle of between 12.24° and 12.30°, a 150-m diameter asteroid, initially traveling at 11.2 km/s, might potentially survive its entire atmospheric flight without fragmentation. Characteristically, we find for these conditions, that the maximum ram pressure varies between $40 < P_{ram}$ (MPa) < 60, with the impact velocity being of order 5 km/s and the horizon impact angle being between 3° and 5°. Essentially these critical entry angle conditions result in the development of extremely long atmospheric flight paths (varying from between 3,000 and 9,000 km in length) that facilitate the more gradual and less catastrophic deceleration of the impactor. The capture condition, however, is very sensitive to the initial velocity (see e.g., Hills and Goda 1997) and entry angle, and the non-fragmentation, temporary capture model solutions (that is solutions with the maximum ram pressure being no larger than $\sim$60 MPa) are only available in a very small region of our exploratory phase space. Indeed, this scenario requires the initial velocity to be in the range 11.2 to $\sim$13.0 km/s and the entry angles to fall between 12.24° and 13.35°. For velocities larger than $\sim$13 km/s only atmospheric fragmentation modes appear to be possible. While about 10 % of Earth approaching asteroids are likely to encounter the atmosphere with a velocity in the range 11.2 to $\sim$13 km/s (see e.g., Jeffers et al. 2001; Fang and Margot 2011), only about 1 in 120 such impacts will likely fall within the restricted range required for the entry angle.

Given the absence of any detailed theory for the break-up of large bodies under the conditions imposed by atmospheric deceleration, and indeed, even in light of the few observational studies that do exist for small sized meteoroids, there appears to be no specific physical reason to exclude the non-fragmentation scenario—that is scenario (1)—

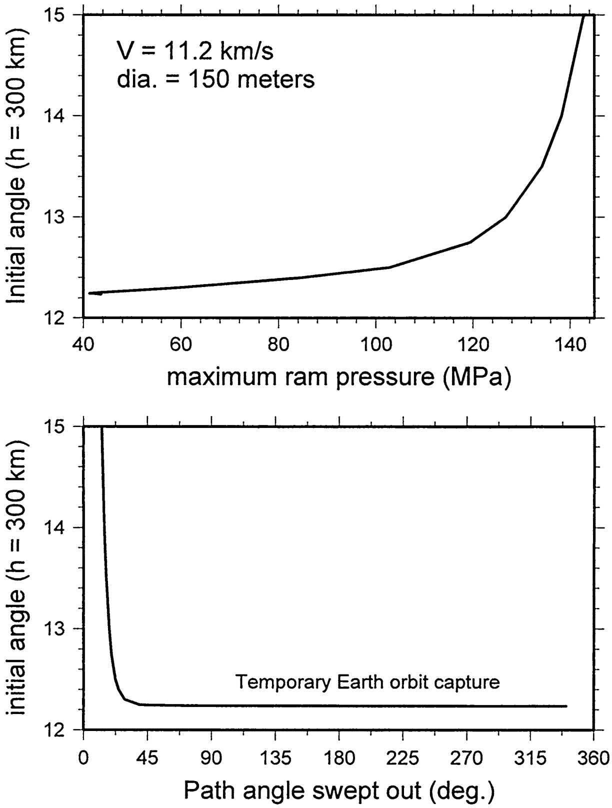

Fig. 4 (*top*) Maximum ram pressure experienced as a function of the initial entry angle. (*bottom*) Angular path length, as swept out from the Earth's center, against initial entry angle. In each case the initial velocity is 11.2 km/s, and the initial asteroid diameter is 150-m. For entry angles smaller than 12.2° no ground impact takes place

from being a potential explanation for the origin of the Rio Cuarto craters. While the temporary Earth-orbiting capture of a small asteroid will happen only rarely, such events do appear to have occurred within recent recorded history. Remarkably, another Argentinean fall, the IAB octahedrite Campo del Cielo (CdC) meteorite, offers an example of an extensive strewn field, along with an associated series of some 22 impact craters (spread over a region 18-km long and 4 km-wide) that were produced by a series of low-velocity, oblique ground impacts into loess (Wright et al. 2006). Indeed, a recent study by Visconi et al. (2011) of the penetration funnels associated with a number of new meteorite finds within the CdC strewn field revealed ground impact angles varying from 9° to 16° to the horizon. In the case of the CdC crater field it is clear that the parent body fragmented during atmospheric flight, and it would accordingly appear to be an analogous instance of our scenario (2), although the progenitor body in CdC case would have been only about 10 m across (Liberman et al. 2002). The great (also called Chant) fireball procession, observed in 1913, is a another good example of what appears to have been a temporary Earth-orbit capture event, with, in this case, a whole train of continuously forming and then ablating fragments being observed over a ground path that exceeded 11,000 km in length

(Chant 1913; O'Keefe 1959; Olson and Hutcheon 2013). Other similar such fireball processions, traversing thousands of kilometers, are also reported to have occurred on, for example, August 18, 1783 (see, e.g., Beech 1989), and on July 20, 1860 (Lyman 1860). The Earth-grazing daylight fireball of August 10, 1972 further provides another example of a long atmospheric passage, of, in this case, a meter-sized object traversing an atmospheric path of at least 1,500 km. In this latter case, however, the angle of encounter did not allow for full capture and the object returned to interplanetary space without impacting the ground (Ceplecha 1994).

Hills and Goda (1997) have studied the conditions under which temporary Earth orbit capture might take place for asteroids with diameters between 1 and 20 m and they find that a highly restrictive set of conditions must be imposed if immediate ground impact or escape back into interplanetary space is to be avoided. Indeed, Hills and Goda argue that in the small asteroid range only 0.1 % of grazing impacts might result in temporary capture, and this percentage rapidly decreases towards zero as the initial encounter velocity increases from 12 to 15 km/s. While grazing and temporary orbital capture events are certainly going to be rare, it is none the less suggested that, albeit it statistically unlikely, they are feasible initial conditions for a progenitor body capable of producing the Rio Cuarto crater field.

6 Discussion and Conclusions

In terms of ground-based investigations, Schultz et al. (1994) have studied the detailed chemistry of impact breccias recovered from the Rio Cuarto craters. Interestingly, they find evidence to suggest that the non-terrestrial material component mixed-in with the breccias increases as one moves southwest from crater A to craters E and D and beyond. Interpreting this result in terms of enhanced mixing of projectile material at lower velocities in the downrange direction, the clear implication is that the direction of travel was from the northeast to southwest. This direction of travel corresponds by necessity to scenario (1), and to allowed versions of scenarios (3) and (4). Scenario (2), even thought it requires a southwest to northeast direction of motion, is also consistent with the apparent variation in the mixing ratio of target to projectile material since the impact velocity of the smaller, uprange, fragments are significantly lower than those of their downrange, more massive companions (see column 7 of Table 1). In the case of scenario (2), however, one would expect there to be some significant ejection of material to the northeast of crater A and yet none is apparently observed. We have additionally noted that it is not clear under scenario (2) how the interaction of bow shocks model (Passey and Melosh 1980) can accommodate the large ~ 10 km lateral spread in the locations of craters I and J, and K. Furthermore, we have argued on probabilistic grounds that scenarios (3), (4) and (5) are the more unlikely explanations for the Rio Cuarto crater field, and while those who throw stones should not live in glass houses, we accordingly conclude that scenario (1), in spite of its required fine-tuning of the initial impact angle condition, does provided the best (all be it still highly improbable) impact model explanation to the available data. This scenario requires the arrival to the ground of a substantially intact 100–150 m diameter, ordinary chondrite composition, asteroid that is decapitated in the production of crater A. Substantial additional material and indeed several sizeable 10–75 m diameter fragments are then sent downrange to produce craters B through K—to incorporate the lateral spread between craters I, J and K, the downrange spray angle of ejecta material from crater A would need to be of order 20°. Our analysis indicates that if temporary Earth capture is allowed for then a 150-m diameter asteroid might potentially impact the ground largely intact at an angle of about 5° to the horizon with an impact speed of order 5 km/s. Hydro-code and direct laboratory studies indicate that projectile decapitation is the most likely outcome in the event of a very low angle impact (see, e.g., Gault and Wedekind 1978; Schultz and Gault 1990; Davison et al. 2011; Schultz et al. 2012; Elbeshausen and Wünnemann 2013), and such studies also indicate that the fragments produced during decapitation retain a significant fraction of the initial impactor's speed, thereby accommodating the generation of additional downrange craters.

In conclusion, of the five impact scenarios considered in this article it is suggested that the single-body, shallow-angle impactor model (scenario 1) most readily accounts for the observations relating to the Rio Cuarto structures. This model, however, is dependent upon the improbable, but certainly possible, fine-tuning of the initial Earth-atmosphere entry conditions. This result does not prove, *per se*, that the Rio Cuarto structures were produced by an impact; it simply indicates that their origin via an asteroid impact is a distinct possibility—rather than an absolute impossibility. While alternative formation scenarios for the origin of the Rio Cuarto structures are certainly possible, if not more probable than the impact model, there still remain important ground details to clarify. To move further forward in understanding the Rio Cuarto structures it will be necessary to fully resolve the debate concerning their physical age (a few thousand years vs. several hundred thousand years), and it will be necessary to demonstrate, beyond all reasonable doubt, that they are morphological distinct features with respect to the aeolian deflation basins that are additionally distributed across the Pampean plane. Likewise, it will be necessary to further map out the various impact glass horizons in the greater region, and to better understand their exposure, erosion and transport/mixing histories. Furthermore, new and extensive ground surveys might fruitfully be conducted to see if any evidence for a distinct meteorite strewn field, with an age commensurate to that of the Rio Cuarto craters, truly exists.

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