Ground truth for oblique impact processes: New insight from the Rio Cuarto, Argentina, crater field

Peter H. Schultz Department of Geological Sciences, Brown University, Providence, Rhode Island 02912
Christian Koeberl Institute of Geochemistry, University of Vienna, A-1010 Vienna, Austria
Theodore Bunch NASA Ames Research Center, Moffett Field, California 94035
John Grant, William Collins Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

ABSTRACT

New evidence for an impact origin of oblong rimmed depressions near Rio Cuarto, Cordoba Province, Argentina, includes shocked silicate phases (e.g., diaplectic glass), thermal decomposition of high-temperature mineral clasts (e.g., baddeleyite from zircon), rapid quenching, very low water contents (≤0.1 wt%), and generation of identical glasses in hypervelocity laboratory impact experiments. The results indicate that glasses with a wide range in major element concentrations can form from a single target type in a relatively small impact event. Impact glasses with the greatest volatile loss typically exhibit the greatest meteoritic contamination (as defined by Cr, Ni, and Ir abundances). The different impact glass types and the different degrees of impactor contamination are proposed to reflect proximity to the projectile-target interface during shallow penetration in an oblique impact, consistent with laboratory simulations and planetary analogues.

INTRODUCTION

G. K. Gilbert showed in 1893 that the most likely impact angle on a planetary body should be near 45°, with decreasing frequencies at higher and lower angles from the horizontal (Gilbert, 1893; Shoemaker, 1962). Oblong craters produced by very low angle (<10°) impacts are not only statistically less likely but also are more rapidly erased on Earth by erosion, owing to their smaller size and shallower penetration depths. A series of rimmed elongate depressions in the loessoid deposits of the Pampas of Argentina north of Rio Cuarto (lat 32°50′S, long 64°10′W), however, closely resembles the pattern produced by oblique hypervelocity impacts not only in laboratory experiments but also on planetary surfaces. Preliminary geochemical and petrographic analyses of impact glasses and a chondritic meteorite fragment supported this analogy (Schultz and Lianza, 1992). Here we present new evidence for the impact origin, assess the range of impact products, and examine the oblique impact processes through comparison with experimental impact glasses.

SAMPLES AND METHODS

Several different types of glasses were found around or within six (of eleven) of the oblong Rio Cuarto structures: vesicular layered or folded glass, vesicle-poor splash forms, and hollow microspheres. Most common are vesicular glasses, which contain abundant mineral clasts from the loess. Many are fragments of larger glassy bombs; the largest fragment exceeds 0.5 kg. Smaller samples exhibit folds or zones of elongated vesicles indicating plastic flow and have a layered appearance. Upper surfaces usually preserve a tachylitic sheen, whereas lower surfaces resemble sand casts. Vesicle-poor splash-form glasses generally are elongate in the form of drops or twisted green glass containing schlieren and flows of contrasting hardness and refractive indices. They contain fewer mineral clasts but may be rimmed by a more vesicular and clast-rich zone. These glasses do not have any of the characteristics (e.g., tubular structure) typical of fulgurites. Spherules (1–2 cm across) containing swirled patterns also have been recovered. Much smaller (33–100 μm) hollow spherules and spherule fragments are in the upper 50 cm of the loess in the region. Numerous small glass shards composing 75% of the finer fractions of the loess (<11 μm) occur throughout the Pampas. Although their composition is consistent with wind-transported volcanic materials from the west (Teruggi, 1957), more detailed isotopic studies are necessary to distinguish between such volcanic glasses and possible impact-derived glasses.

Two chondritic fragments were also recovered from one of the large, elongate Rio Cuarto depressions on separate trips to the site. The smaller meteorite exhibits a flangelike melt rim (Schultz and Lianza, 1992), which is absent in the second, larger fragment. Both meteorites contain essentially identical olivine (Fa_{18}) and orthopyroxene (Fs_{17}) (mean deviation <3%) and are classified as H4/H5-type chondrites. The flanged melt rim of the smaller chondrite is unlike chondritic ablation rims produced during atmospheric entry in several respects. First, unlike ablation rims, the Rio Cuarto meteorite melt rim contains large acicular olivine quench crystals, partly devitrified glass, irregular FeNi metal–FeS blebs containing eutectoid textures, and spinels that lack reaction rims or elemental diffusion. Second, the Rio Cuarto meteorite melt rim is remarkably homogeneous and without significant vesiculation, unlike the two to three compositional and textural zones (e.g., scoriaceous outer part with vesiculation) associated with typical ablation rims (Ramdohr, 1967). Third, the oxygen fugacity inferred from FeNi-FeS globules within the Rio Cuarto melt rim is much lower than the fugacity for ablation rims formed on chondrites during atmospheric entry. The low oxygen fugacity is consistent, however, with conditions in an ionized vapor cloud produced during an oblique impact (Schultz and Gault, 1990). The Rio Cuarto meteorite melt rim appears to be a unique impact product.

Petrography and geochemistry of impact glasses and target materials were studied by optical microscopy, electron-microprobe analysis, and neutron-activation analysis. The water content of selected impact glasses was measured by infrared (IR) spectrometry, with a detection limit of about 0.001 wt%, following methods described by Koeberl and Beran (1988). Synthetic reference glasses were produced by quenching bulk loess after heating (at 1 bar in a platinum crucible) at 930 °C for 3 h, at 1168 °C for 30 min, and at 1335 °C for 3 h. In addition, hypervelocity, oblique-impact experiments were performed by using the NASA Ames Vertical Gun Range (AVGR). Three types of 0.635-cm-diameter projectiles (aluminum, Pyrex, and Rio Cuarto chondrite) were shot into Rio Cuarto loess at 5 km/s at an angle of 15° from the horizontal under near-vacuum (0.6 torr) conditions.

RESULTS

The Rio Cuarto glasses petrographically resemble impactites from known impact craters and show abundant evidence for an impact origin. Vesicle-poor splash-form glasses contain lechatelierite (Fig. 1A) and diaplectic glass (Fig. 1B), thereby indicating shock levels of 40–50 GPa (Stöffler, 1972). The numerous minor minerals composing the loess trapped in the impact glasses provide excellent signatures of shock metamorphism. High melt temperatures are indicated by the presence of baddeleyite, which results from the decomposition of zircon to $ZrO_2 + SiO_2$ (Fig. 1C) at temperatures of 1720 to 1900 °C (El Goresy, 1965). Loess is poor in quartz (2–20 wt%, Teruggi, 1957), and its high porosity leads to locally high shock-induced temperatures (Kieffer, 1971). Thus, the full range of subsolidus shock effects is not observed. Nevertheless, some rare quartz grains showing planar deformation features have been found. An alternative record of various shock levels experienced by the target materials can be obtained by studying titanomagnetite (Stöffler et al., 1988), which occurs in the loess. A full range of shock signatures is found within the Rio Cuarto glasses, from grain-margin melt reaction to total melting and dendritic crystallization of secondary Fe-Ti phases. Other shock and/or thermal effects observed in the Rio Cuarto glasses include decomposition of magnesian olivine, partially melted or resorbed margins of calcium pyroxenes (Fig. 1D), thermal breakdown of amphiboles, and partial decomposition of sphene. None of the glasses shows evidence for mixing with the underlying country rock, only 15–20 m below the surface.

Clast-rich vesicular glasses were found to contain about 0.12 wt% water, whereas the splash-form glass contained only 0.06 wt% water. Such values typify impact glasses (Koeberl and Beran, 1988). Green vesicular clast-free glasses found in the loess more than 500 km downrange to the southeast yielded a much lower water content (0.003 wt%). Although these distant green glasses cannot yet be unequivocally related to Rio Cuarto, their composition is very similar to some of the Rio Cuarto glasses.

In the synthetic glass experiments, heating the bulk loess to 930 °C for 3 h failed to form glass. Heating to 1168 °C (FL-1168) for 30 min produced a glass similar to the Rio Cuarto vesicular clast-rich glasses, whereas heating to 1335 °C (FL-1335) for 3 h produced a homogeneous glass more analogous to the splash-form glasses. The average composition of the matrix glasses of FL-1168 provides a reference for the Rio Cuarto and experimental impact glasses and is taken as the bulk composition of the loess. Composition of the FL-1335 synthetic glass closely resembles the clast-poor splash-form Rio Cuarto glasses, but most Rio Cuarto clast-rich vesicular glasses exhibit a feldspathic composition (lower CaO and MgO with elevated Na_2O and K_2O). Clast-poor or clast-free Rio Cuarto samples also contrast with the synthetic glasses by exhibiting elevated levels of refractory CaO and MgO with significantly depleted volatile fractions, Na_2O and K_2O.

Glasses produced in the AVGR oblique-impact experiments into loess have compositions closely resembling the Rio Cuarto glasses (Fig. 2). Clast-free AVGR glasses morphologically resembled miniature versions of the splash-form glasses from Rio Cuarto and had elevated CaO and MgO relative to the bulk loess. These experiments clearly document that the observed range in compositions for the Rio Cuarto glasses can be generated from a single target material.

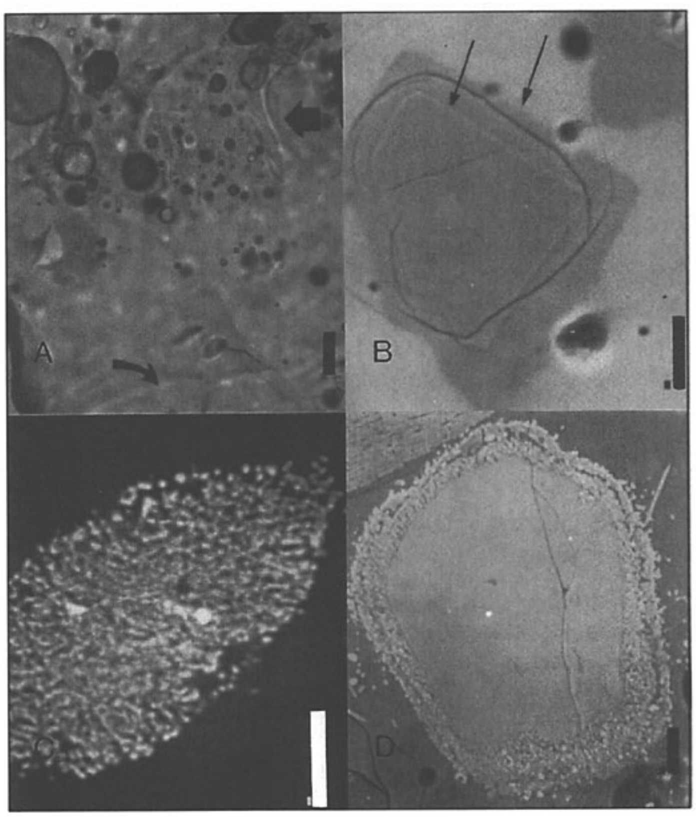

Figure 1. Petrographic shock indicators within Rio Cuarto glasses. A: Photomicrograph showing lechatelierite (thick arrow) and flow features (thin arrow) characteristic of rapidly quenched impact glasses formed under high pressures (>50 GPa). Scale bar represents 100 μm. Smallest arrow (upper right) indicates partially melted quartz. B: SEM-BSE image of quartz partly transformed to diaplectic glass (right arrow), enclosed by matrix-melt glass (left arrow points to interface). Scale bar represents 10 μm. C: SEM-BSE image of baddeleyite produced from thermal decomposition of zircon. Scale bar represents 100 μm. D: SEM-BSE image showing reaction-rim melt of calcium pyroxene in quartz. Scale bar represents 10 μm.

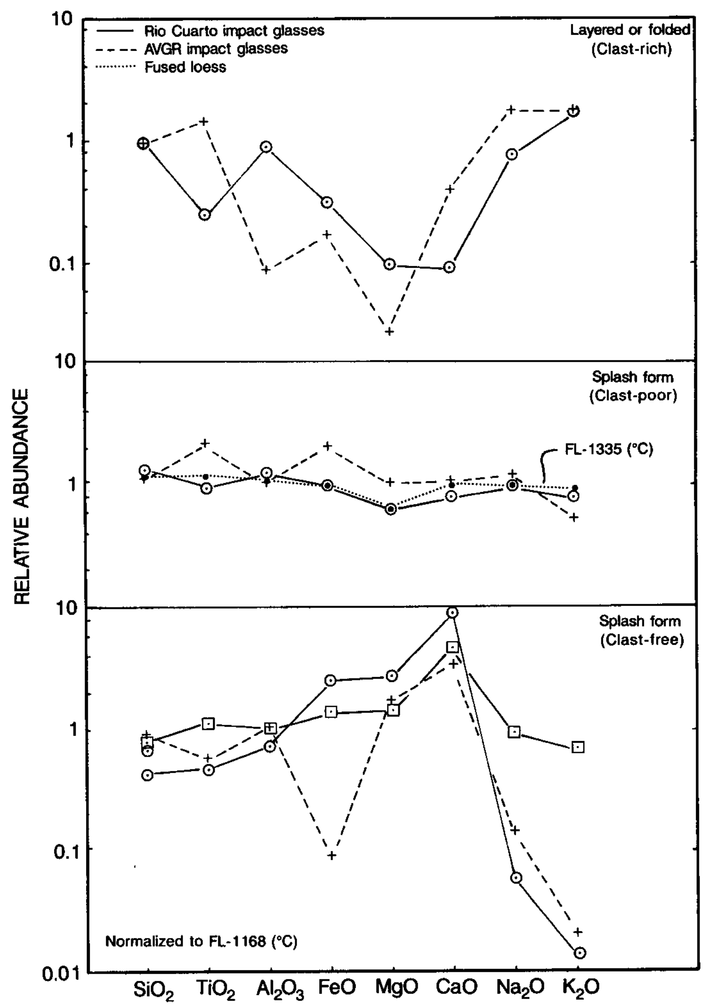

Figure 2. Relative abundances of major oxides in interstitial glasses from Rio Cuarto impact site and products of heating and impact experiments normalized to fused loess (heated to 1168 °C for 30 min). Lower plot shows two different clast-free impact glasses.

The recovery of two chondritic meteorites at Rio Cuarto allows testing for a meteorite signature in the impact glasses and permits assessing its dissemination. As is typical of impact melt rocks in general (Palme, 1982), the siderophile trace element concentrations in most Rio Cuarto impact glasses are only slightly higher than target rock values. Fractionation of the siderophile element distribution patterns can occur prior to (Mittlefehldt et al., 1992) and after (Palme, 1982) incorporation in the impact melt, which also seems to be the case for Rio Cuarto impact glasses. Some glasses exhibit high Cr concentrations (>1000 ppm) and contain pyrrhotitic spherules with high Ni (1–2 wt%), which may indicate dispersed relicts of the impactor. One glass contains metallic Fe and Fe-Ni spherules rimmed by high CaO blebs, having high Cr (2000 ppm) and MnO (7 wt%). The Ir/Au ratios for selected Rio Cuarto impact glasses are consistent with ratios (Ir/Au = 1–3) observed in glasses and melts from other impact sites and contrast with values (Ir/Au = 0.2) for terrestrial materials (Palme, 1982).

DISCUSSION

Although it is possible to fuse loess at relatively low temperatures by fluxing with organic material (Bloom, 1992), the resulting product does not exhibit the clear matrix glass, the distinctive schlieren, immiscible blebs, melt-reaction rims, petrographic indicators of high shock and thermal levels, the low water content, and the meteoritic signatures. Such low-temperature melts also contained significant residual carbon. Small glassy samples ("escoria") found elsewhere in Argentina (courtesy of A. Bloom) exhibit clast-laden feldspathic glass but do not show any evidence for shock, which was found in the Rio Cuarto impact glasses. Thus, these Rio Cuarto glasses cannot be the result of human activity or other low-temperature events, e.g., brush fires, as suggested by Bloom (1992).

Deflation hollows are common in certain regions of the Pampas and provide an alternative analogue for the Rio Cuarto depressions (Schultz and Lianza, 1992; Bloom, 1992). The eolian system, however, forms an arcuate pattern that parallels the Rio Cuarto structures far to the southeast but is perpendicular just 100 km to the south (Iriondo, 1989). There is little question that the structures have been subject to eolian reworking (Grant and Schultz, 1992). Because their morphology also closely resembles patterns produced by oblique impacts both in the laboratory and on the planets, morphology alone results in a nonunique interpretation. The discovery of shocked minerals and high-temperature melting products provides very good evidence for an impact origin, while the oblique-impact analogy provides a reasonable context for understanding the range in glass compositions and levels of meteoritic contamination.

The three types of Rio Cuarto impact glasses reflect different pressure and temperature histories. Figure 3 shows that the composition of layered impact glasses (with FeO < 20 wt%) generally resembles the low-temperature synthetic glass (FL-1168) but forms a different mixing trend with the Rio Cuarto chondrite melt rim as one end member. Most splash-form impact glasses (Fig. 3B) cluster tightly around values for the higher-temperature synthetic glass (FL-1335 in Fig. 3A). Clast-free glasses, however, resemble the ropy AVGR impact glasses, which are strongly depleted in K_2O and have higher CaO and MgO contents relative to the experimentally fused loess.

The feldspathic interstitial glass in the layered samples closely resembles the composition of individual glass shards, which dominate the finest fraction of the loess. The close match of the feldspathic glasses with the trend of FL-1168 (Fig. 3A) is consistent with a lower-temperature process that melts this silicate fraction and some minerals while selectively removing the carbonates and water by vaporization. Laboratory experiments document enhanced vaporization of volatile-rich targets by hypervelocity oblique impacts because of the role of mechanical shear heating (Schultz and Gault, 1990). The steep trend of Rio Cuarto impact glasses relative to the synthetically fused loess, however, suggests a different end member resembling the melt rim of the chondrite and/or fractionation due to the impact process.

In contrast to the layered glasses, compositions of the splash-form glasses are similar to values for FL-1335 (Figs. 2, 3). Their narrower compositional range, petrographic evidence for higher shock-temperature levels, and low water content (0.06 wt%) all indicate rapid, intense heating (>1600 °C) and quenching. The composition of the clast-free splash-form glasses, however, is similar to the ropy glasses produced in hypervelocity impact experiments. Glasses with low SiO_2/MgO ratios depart from the trend of the

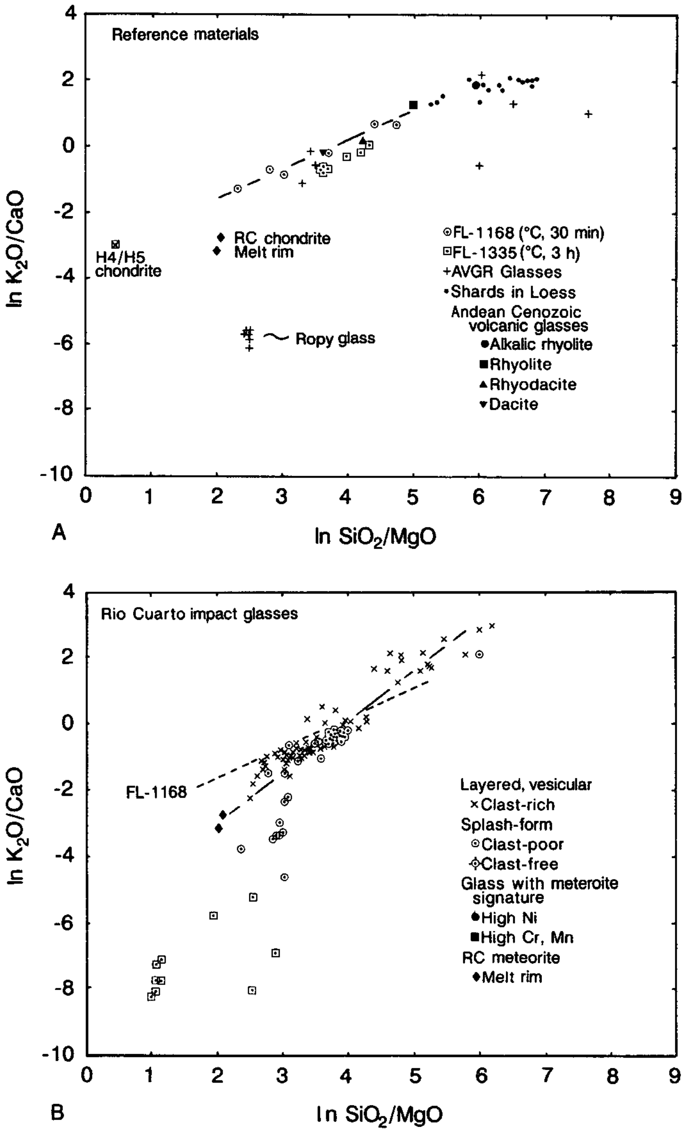

Figure 3. A: Comparison of volatile (K_2O and SiO_2) with refractory (CaO and MgO) components of clear interstitial glass within bulk loess fused at 1168 °C for 30 min; loess fused at 1335 °C for 3 h; glasses recovered from hypervelocity (5 km/s), oblique-impact (15°) experiments at Ames Vertical Gun Range (AVGR) using loess as the target; and glass shards comprising the fine fraction of loess. Bulk loess fused at lower temperatures (FL-1168) exhibits a range of values similar to Cenozoic volcanic products (from Schmitt-Riegraf and Pichler, 1988), whereas loess fused at higher temperatures (FL-1335) clusters more tightly below this trend because of more complete melting and mixing of loess clasts. RC = Rio Cuarto. B: Comparison of volatile and refractory oxide ratios for interstitial glasses in different types of Rio Cuarto impact glasses (with FeO < 20 wt%).

vesicular glasses (Fig. 3B). This change in slope is most likely the result of melt-vapor fractionation in which volatile K_2O and Na_2O are lost, thereby concentrating the refractory CaO and MgO, as also found in stepwise high-temperature experiments (Walter and Carron, 1964; Yakovlev and Basilevsky, 1994). These most fractionated samples were to the south of the Rio Cuarto craters and may represent the highest-velocity component directed downrange, perhaps analogous to the proposed origin of the moldavites from the Ries crater (Engelhardt et al., 1987).

Meteoritic signatures in the glasses generally increase with increasing volatile loss and refractory concentration (Fig. 3B). Higher abundances of the siderophile element Ni are generally in glasses having K_2O/CaO ratios typical for the splash-form glasses, whereas the more lithophilic element Cr is relatively more abundant in glasses with low K_2O/CaO ratios. Both the Ni/Fe ratio and Cr contents increase as the SiO_2/MgO ratio decreases, as expected from fractionation or incorporation of meteoritic MgO. Low-angle impact experiments using parts of the Rio Cuarto chondrite as a projectile result in similar fractionation of Cr and Ni, perhaps owing to projectile decapitation prior to complete target penetration (Schultz and Gault, 1990). The decapitated projectile fragments impact downrange at angles and velocities slightly lower than those of the original impactor, allowing enhanced mixing of the projectile with the target materials.

The observed glass compositions and dissemination of the chondritic meteorite component for the clast-poor splash-form Rio Cuarto impact glasses are interpreted to reflect both proximity to the projectile-target interface and high temperatures during shallow penetration by a low-angle impactor. In contrast, the layered or folded glasses are formed at lower shock levels from shear-heated target materials at a greater distance from the projectile-target interface. Just as observed in experiments (Gault and Wedekind, 1978) and inferred from low-angle impacts on the Moon and Venus (Schultz, 1992), most melt and early ejecta at Rio Cuarto were sprayed downrange, leaving relatively little melt inside the crater. The range in Rio Cuarto glass compositions (Fig. 3B) is narrower than that of the experimental impact glasses, but broader than that of the synthetic glasses. This contrast reflects the time available for mixing during heating, which in turn depends on the scale of the event. Large-scale oblique impacts should result in compositional trends tighter than the Rio Cuarto trend owing to longer mixing times, but such impacts could exhibit distinct compositional groupings because different stratigraphies are sampled during impactor penetration.

CONCLUSIONS

The Rio Cuarto crater field and comparison with experimental impact glass provide a unique opportunity to document the chemical and physical range in impact products and impactor fate from a compositionally simple target and known impactor. The composition and distribution of glasses further allow assessing the relative roles of heating by shock or mechanical shear as well as of proximity to the projectile-target interface during shallow penetration by the low-angle impactor. Such processes contribute to the glass types, petrographic characteristics, compositional range, and impactor dissemination found in the Rio Cuarto glasses.

ACKNOWLEDGMENTS

Supported by National Science Foundation grant EAR-9121347 and NASA grant NAGW-705. Schultz is grateful for use of the Keck–National Science Foundation Microprobe Facility (Brown University) and the assistance of J. Devine. We thank A. Beran and L. Kerschhofer (University of Vienna) for help with the water determinations; A. Bloom for providing samples of escoria and for discussion of alternatives; numerous Argentine colleagues and friends (R. Lianza, E. Avaca, M. Diaz, L. Incatasciato, J. P. Lopez, A. Toselli, Cdr. A. Ruggiero, M. Iriondo, and T. G. Castellanos), who assisted in the field survey of the site by Schultz, Grant, and Collins; and R. Grieve, R. Anderson, T. Watters, and an anonymous reviewer for their helpful comments on this manuscript.

REFERENCES CITED

Bloom, A., 1992, A non-impact explanation for elongate depressions near Rio Cuarto, Cordoba Province, Argentina: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A136–A137.

El Goresy, A., 1965, Baddeleyite and its significance in impact glasses: Journal of Geophysical Research, v. 70, p. 3453–3456.

Engelhardt, W. von, Luft, E., Arndt, T., Schoch, H., and Weiskirchner, W., 1987, Geochimica et Cosmochimica Acta, v. 51, p. 1425–1443.

Gault, D. E., and Wedekind, J. A., 1978, Experimental studies of oblique impacts, *in* Proceedings of the Lunar and Planetary Science Conference, 9th: New York, Pergamon, p. 3843–3875.

Gilbert, G. K., 1893, The Moon's face; a study of the origin of its features: Washington Philosophical Society Bulletin, v. 12, p. 241–292.

Grant, J., and Schultz, P. H., 1992, Gradation of the Rio Cuarto crater field, Argentina: *in* Lunar and Planetary Science XXIII: Houston, Texas, Lunar and Planetary Institute, p. 439–440.

Iriondo, M., 1989, A late Holocene dry period in the Argentine plains, *in* Rabassa, J., ed., Quaternary of South America and Antartic Peninsula, Volume 7: Rotterdam, Netherlands, A. A. Balkema, p. 197–218.

Kieffer, S. W., 1971, Shock metamorphism of the Coconino Sandstone at Meteor Crater, Arizona: Journal of Geophysical Research, v. 76, p. 5449–5473.

Koeberl, C., and Beran, A., 1988, Water content of tektites and impact glasses and related chemical studies, *in* Proceedings of the 18th Lunar and Planetary Science Conference: Houston, Texas, Lunar and Planetary Institute, p. 403–408.

Mittlefehldt, D. W., See, T. H., and Hörz, F., 1992, Dissemination and fractionation of projectile materials in the impact melts from Wabar Crater, Saudi Arabia: Meteoritics, v. 27, p. 361–370.

Palme, H., 1982, Identification of projectiles of large terrestrial impact craters and some implications for the interpretation of Ir-rich Cretaceous/Tertiary boundary layers, *in* Silver, L., and Schultz, P., eds., Geological implications of impacts of large asteroids and comets on the Earth: Geological Society of America Special Paper 190, p. 223–233.

Ramdohr, P., 1967, The fusion crust of meteorites: Earth and Planetary Science Letters, v. 2, p. 197–209.

Schmitt-Riegraf, C., and Pichler, H., 1988, Cenozoic ignimbrites of the central Andes: A new genetic model, *in* Bahlburg, H., et al., P. eds., the southern Central Andes: Berlin, Springer-Verlag, p. 183–197.

Schultz, P. H., 1992, Atmospheric effects on ejecta emplacement and crater formation on Venus from Magellan: Journal of Geophysical Research, v. 97, p. 16,183–16,248.

Schultz, P. H., and Gault, D. E., 1990, Prolonged catastrophe from oblique impacts, *in* Sharpton, V. L., and Ward, P., eds., Global catastrophes in Earth history: An interdisciplinary conference on impacts, volcanism, and mass mortality: Geological Society of America Special Paper 247, p. 239–261.

Schultz, P. H., and Lianza, R., 1992, Recent grazing impacts on the Earth recorded in the Rio Cuarto crater field, Argentina: Nature, v. 355, p. 234–237.

Shoemaker, E., 1962, Interpretation of lunar craters, *in* Kopal, Z., ed., Physics and astronomy of the Moon: New York, Academic Press, p. 283–351.

Stöffler, D., 1972, Deformation and transformation of rock-forming minerals by natural and experimental shock processes, I, Behavior of minerals under shock compression: Fortschritte der Mineralogie, v. 49, p. 50–113.

Stöffler, D., Bischoff, A., Buchwald, V. F., and Rubin, A. E., 1988, Shock effects in meteorites, *in* Kerridge, J. F., and Matthews, M. S., eds., Meteorites and the early Solar System: Tucson, University of Arizona Press, p. 165–202.

Teruggi, M. E., 1957, The nature and origin of the Argentine loess: Journal of Sedimentary Petrology, v. 27, p. 322–332.

Walter, L. S., and Carron, M. K., 1964, Vapor pressure and vapor fractionation of silicate melts of tektite composition: Geochimica et Cosmochimica Acta, v. 28, p. 937–951.

Yakovlev, O. I., and Basilevsky, A. T., 1994, Experimental studies of geochemical aspects of impact cratering, *in* Dressler, B. O., et al., eds., Large meteorite impacts and planetary evolution: Geological Society of America Special Paper 293 (in press).

Manuscript received March 24, 1994
Revised manuscript received June 21, 1994
Manuscript accepted June 30, 1994