the BSB-$S_2$/THPMA-MMA material system can be used to pattern complex 3D structures and suggests that microfluidic structures and even microoptical structures, such as gratings, waveguides, and photonic lattices, can be fabricated readily. The low irradiation power used to pattern the structure also demonstrates the high two-photon sensitivity of this microfabrication material system.


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26. Freestanding microstructures were fabricated (*2*, *28*) by irradiating solid thin films of 1 weight % (wt %) BSB-$S_2$ in SU-8 using tightly focused [numerical aperture (NA) = 1.4] 80-fs pulses (at an 82-MHz repetition rate, 745 nm) at average powers as low as 2.4 mW and then dissolving the unexposed resin in an organic solvent.
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# A Possible Tektite Strewn Field in the Argentinian Pampa


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**Impact glass associated with 11 elongate depressions in the Pampean Plain of Argentina, north of the city of Río Cuarto, was suggested to be proximal ejecta related to a highly oblique impact event. We have identified about 400 additional elongate features in the area that indicate an aeolian, rather than an impact, origin. We have also dated fragments of glass found at the Río Cuarto depressions; the age is similar to that of glass recovered 800 kilometers to the southeast. This material may be tektite glass from an impact event around 0.48 million years ago, representing a new tektite strewn field.**


Comets and asteroids that impact planets create circular craters at impact angles between ~15° and 90° (measured from the surface); when the angle θ is less than ~15°, craters become elongate in shape. On Earth, the only confirmed low-angle impact structures are the series of elongate craters at Río Cuarto, Argentina, estimated to be <0.01 million years (Ma) (*1*) to <0.005 Ma (*2*, *3*) in age. Río Cuarto is also the largest object known to have impacted Earth in the last 0.1 Ma, an impact that may have been witnessed by early inhabitants of the Pampean Plain (*1*). The largest feature (64°10′W, 32°45′S) has dimensions of 4.5 km by 1.1 km and is considered to correspond to the first impact; an impactor initially 150 to 300 m in diameter then fragmented and ricocheted to the south to produce 10 additional elongate depressions (*1*). Impact formation of the depressions was questioned (*4*), but samples of meteorite, and detailed analysis of glass fragments found at the site, supported the impact hypothesis (*1*, *5*).

Río Cuarto glass is typically vesicular, with abundant loess inclusions, and lower surfaces that appear to be sand casts (*1*, *5*). Vesicle-poor splash forms (elongate drops) are also common (*1*, *5*). Although most samples do not show evidence of much meteoritic contamination, some fragments exhibit high Cr [>1000 parts per million (ppm)] and Ni (1 to 2 weight %) concentrations, and one has metallic Fe and Fe-Ni spherules (*5*). Siderophile-element abundance and rare earth element pattern suggest a chondritic impactor (*6*). In addition, very low water content (characteristic of tektites and other impact glasses) is typical; vesicular glass contains ~0.1 weight % water, whereas splash-form glass contains 0.06 weight % (*5*). The presence of lechatelierite (*5*), homogeneous oxide distribution, and high silica content are additional characteristics in common with tektites (*1*). Overall, the glass has a composition similar to that of the loessoid sediments that cover the Pampa (*1*, *7*). Because loess only occurs to a depth of <50 m over a metamorphic basement, it was suggested that the glass originated in a low-angle impact that did not excavate deeply (*5*).

We have conducted an extensive remote-sensing study of the Río Cuarto site and the surrounding Pampean Plain, using CORONA and EOS Terra-ASTER multispectral, high-resolution satellite imagery. This survey reveals several hundred elongate depressions with high length-to-width ratios (Figs. 1, S1, and 2); 403 are >200 m in their long axes, 201 >1 km, and 6 >5 km. Long-axis orientations vary throughout the region: north-


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northeast–south-southwest in the north, northeast-southwest in the south, and north-northwest–south-southeast in the west. Field visits to 52 of these features [including several of those previously identified (*1*)] confirm that they are morphologically similar to the original 11 (*1*): Most depressions have rims 3 to 10 m above the surrounding plain, some of which are degraded, and bases 3 to 10 m below the plain. Several elongate features, including those described by Schultz and Lianza (*1*), have a "lag" deposit of local country rocks preserved on the crater floor; these samples, and a hardground layer that is occasionally exposed, appear to be unaffected by impact. In addition, we recovered two meteorites from craters D and E (craters that also yielded abundant glass; the largest sample was 17 cm by 9 cm by 6 cm). Glass was found in two of the new structures, and at a road section 400 km to the south, near the town of Santa Rosa.

Assuming that all the depressions have a similar origin, to account for the hundreds of additional similar features we see would require a larger initial object (>0.5 km in diameter) that perhaps fragmented in the atmosphere before impact and ricochet. Estimates of impact rates for bodies in this size range vary widely, from 0.038 Ma (*8*) to 0.38 Ma (*9*). Such highly elongate features require an impact angle $\theta < 5°$, which occurs only 0.75% of the time (*10*, *11*); a 0.5-km-diameter object should impact Earth at <5° about every 5 to 50 Ma. A 0.5- to 0.7-km projectile also appears to be the minimum-diameter stony body that can penetrate Earth's atmosphere at $\theta < 5°$ (*12*). Impact rates for bodies of the size postulated by Schultz and Lianza (*1*) are more frequent by an order of magnitude, but it appears unlikely that they could penetrate Earth's atmosphere at low angle.

There is an aeolian landform that matches a number of the morphological characteristics of the Río Cuarto craters. Upper Holocene parabolic dunes have been described in the Pampean Plain (*13*). These dunes typically form in semiarid environments around a "blowout," or deflation, where the soil surface has been broken and partially removed (*14*). A dune forms at the downwind edge of the blowout deflation and migrates downwind, the crest extending around the elongated blowout. Deflation of the interior continues, forming an elongate feature with a raised rim and a base that is lower than the surrounding plain (*14*). Before the discovery of impact-related materials (*1*, *3*), the Río Cuarto depressions and those further south were considered to be aeolian in origin (*15*–*17*). The variation in long-axis orientations over the region is difficult to reconcile with the breakup and ricochet of a single impactor, but it supports an aeolian formation mechanism, with long axes consistent with prevailing wind directions recorded by meteorology stations. In the Río Cuarto region, where depressions are oriented north-northeast–south-southwest, observations over 19 years find that 38% of winds blow from the north and 53% from the northeast (*18*). To the southwest, in the region of San Luis where depressions are oriented northeast-southwest, 28% of winds are from the north, 32% from the northeast, and 35% from the east (*19*).

Using accelerator mass spectrometry (AMS), we analyzed cosmogenic $^{14}C$ content in the organic carbon fraction of soil recovered from craters J, D, and E to determine the exposure age of these surfaces (*20*). Our results suggest a maximum age of 0.004 Ma for these features, consistent with previous estimates (*1*–*3*).

Schultz and Lianza (*1*) also described two meteorites found in crater D, both fusion crusted ordinary chondrites, and suggested that they were fragments of the Río Cuarto impactor. We have identified and analyzed two new samples, a weathered ordinary chondrite and a basaltic achondrite, recovered from craters D and E, respectively. AMS analysis reveals a $^{14}C$ terrestrial age of 0.036 ± 0.004 Ma for the chon-


**Fig. 1.** EOS Terra-ASTER satellite images showing (**inset**) a portion of the crater field originally defined by Schultz and Lianza (*1*), and elongate features partially infilled with lakes 60 km to the east.

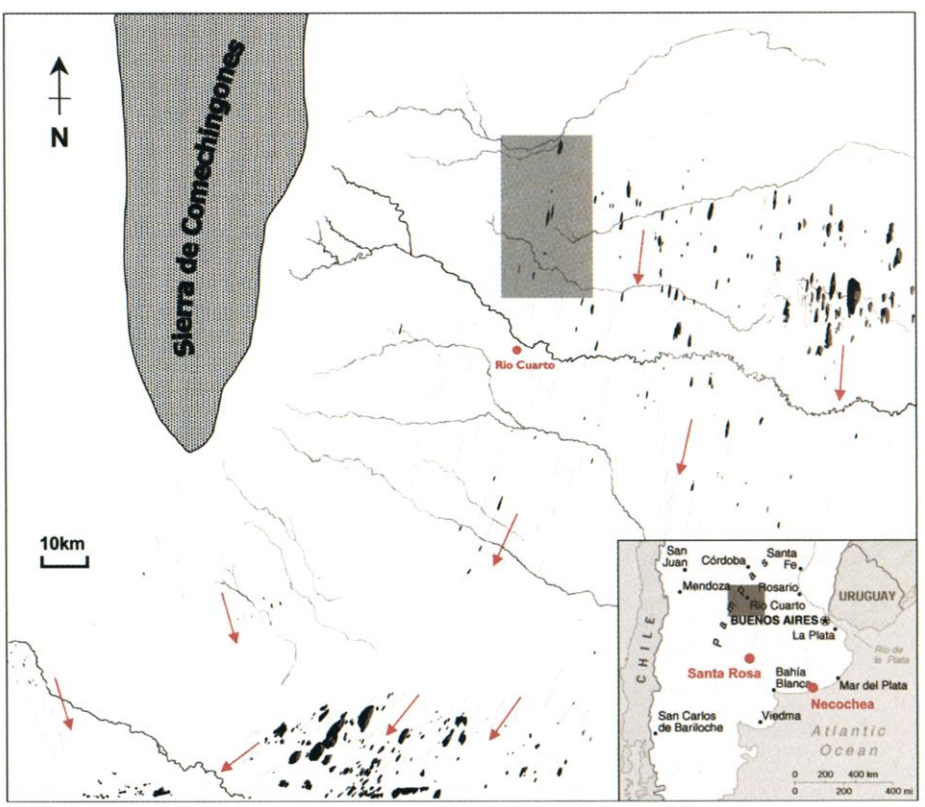


**Fig. 2.** Schematic map of the area, showing elongate features (black), associated lakes (gray), local drainage, and the area originally described by Schultz and Lianza (*1*) (shaded). General orientations of elongate features are indicated by arrows. Additional glass localities (see text) are indicated in red on the context map.

drite, and >0.052 Ma for the achondrite. Variation in terrestrial age and weathering, the recovery of both chondrites and achondrites, and meteorite terrestrial ages older than surface ages for the depressions suggest a meteorite accumulation rather than fragments of a single impactor. Meteorite accumulations are commonly found in blowout deflations (*21*) where samples with a range of compositions and terrestrial ages are revealed after soil is removed.

The geomorphologic and meteoritic evidence suggests that dune formation occurred ~0.004 Ma ago, removing meters of loessoid sediment and exposing rocks previously contained in the sediment column: samples of country rock, meteorites, and any other material deposited onto the surface before deflation. However, it is clear that the glass found at Río Cuarto is derived from an impact; it may therefore be distal, rather than proximal, ejecta. A typical impact (i.e., not highly oblique) producing a 10-km crater might deposit loess-derived glass hundreds of kilometers from the impact site but may itself have been rapidly infilled.

We have attempted to determine the age of this event by Ar-Ar dating of Río Cuarto glass. Analysis of crushed vesicular glass yielded dominantly atmospheric argon. This is typical of highly vesicular impactites (*22*). A sample of inclusion-free Río Cuarto glass yielded much higher radiogenic contents (as much as 75%). Individual fragments of this glass were analyzed by total fusion, the results giving an isochron indicating an age of 0.57 ± 0.1 Ma (2σ error). This is similar to the results obtained with glass from Southern Buenos Aires Province [with an age of 0.46 ± 0.03 Ma (*23*)], found in loess sediments on the coast near the city of Necochea. We suggest that the glass fragments found at Río Cuarto and Necochea were formed by a common impact that occurred at ~0.48 Ma.

We recently recovered glass from a new Pampean locality near the city of Santa Rosa. This material is highly vesicular and has a bulk chemistry (Table 1) intermediate between that of clear and light-brown vesicle-abundant impactite from the Río Cuarto depressions (*1*).

**Table 1.** Major elements from energy-dispersive x-ray microanalysis of Santa Rosa glass (average of six analyses), compared with vesicle-abundant Río Cuarto impactite (*1*).

| | Vesicle-abundant glass | | |
|---|---|---|---|
| | Santa Rosa | Río Cuarto (1) | |
| | | Clear | Light brown |
| $SiO_2$ | 61.2 | 58.4 | 58.3 |
| $Al_2O_3$ | 23.6 | 25.1 | 15.8 |
| MgO | 1.6 | 0.3 | 1.7 |
| $Na_2O$ | 3.6 | 5.4 | 4.3 |
| $K_2O$ | 2.1 | 3.2 | 2.8 |
| CaO | 5.0 | 6.5 | 4.2 |
| $TiO_2$ | 0.3 | 0.0 | 2.0 |
| FeO | 2.7 | 1.4 | 10.3 |

The fact that glass is derived from a thin loess cover does not constrain the size of the buried crater. Tektites originate from the uppermost layer of the target surface (*24*, *25*); however, they may result from relatively large impacts that excavate much deeper craters. Recent modeling studies rule out low-angle impacts as possible causes of tektite strewn fields (*26*). We performed a hydrocode simulation to model tektite production from the impact of a 500-m-diameter projectile at θ = 30°, with an impact velocity of 18 km/s, into a Pampean-like target (a porous 50-m quartzite surface layer over a granitic basement). The final crater produced in this simulation would be ~5 km in diameter (*27*). The results (fig. S2) show that a substantial portion of distal glass ejecta originates from the porous upper layer: 90% of the melt from this layer is ejected early and at high velocity, with little or no contamination from projectile and basement material.

Finally, we can place some lower limit on the spatial distribution of glass from this impact in the Pampean plain. Schultz *et al.* (*3*, *28*) recovered vesicular glass with low water content (0.003 weight %) 500 km downrange of the Río Cuarto depressions and noted that this material and the Río Cuarto glass were of very similar composition. With the Necochea glass (800 km southeast of Río Cuarto) and the Río Cuarto samples displaying similar ages, and the glass we recovered at Santa Rosa (400 km south) and the Río Cuarto samples showing similar composition, this suggests that genetically related glass samples have a wide geographical distribution. Montanari and Koeberl (*29*) identify seven defining characteristics of tektites (*30*) and recommend that the term "tektite" should be reserved for glasses that fulfill most of these criteria. With the recognition that Pampean glass occurs as distal ejecta in a geographically extended strewn field, this material appears to fulfill all other defining criteria for tektites (*30*), so it seems plausible that they are representatives of a widespread tektite strewn field in Argentina with an age of ~0.48 Ma. Further work will determine the extent of this strewn-field, as well as the cogenesis of glass at different locations and of different morphologies, and seek the location of the source crater. The widespread distribution of glass suggests a source crater >5 km in diameter. Given that loessoid sedimentation was ongoing throughout the last 0.5 Ma, we suggest that a recent, possibly well-preserved complex crater remains to be discovered beneath the Pampean Plain of Argentina.

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19. Source: Meteorological Station of the National Institute of Agricultural Technology (INTA, Instituto Nacional de Tecnología Agraria) at San Luis city (33°39′50″S, 65°24′37″W).
20. Samples of soil and paleosol layers were recovered from craters D, E, and J. Although an attempt was made to sample only stable surfaces, soil samples from craters D and E gave recent ages. Samples of soil from an exposed paleosol in the floor of crater J gave the oldest age: 0.004 Ma.
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30. Defining criteria for tektites are as follows (*29*): (i) glassy; (ii) homogeneous rock melts; (iii) contain lechatelierite; (iv) geographically extended strewn-field; (v) distal ejecta, not around source crater or within impact lithologies; (vi) poor in water, and minor extraterrestrial component; (vii) formed from the uppermost layer of the target.


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**Supporting Online Material**
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figs. S1 and S2

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