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Shatter cone and microscopic shock-alteration evidence for a post-Paleoproterozoic terrestrial impact structure near Santa Fe, New Mexico, USA

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ABSTRACT

Field mapping, morphologic description, and petrographic analysis of recently discovered shatter cones within Paleoproterozoic crystalline rocks exposed over an area >5 km^2, located ~8 km northeast of Santa Fe, New Mexico, USA, give robust evidence of a previously unrecognized terrestrial impact structure. Herein, we provisionally name this the "Santa Fe impact structure". The shatter cones are composed of nested sub-conical, curviplanar, and flat joint surfaces bearing abundant curved and bifurcating striations that strongly resemble the multiply striated joint surfaces (MSJS) documented from shatter cones at Vredefort dome. The cones occur as a penetrative feature in intrusive igneous and supracrustal metamorphic rocks, are unusually large (up to 2 m long and 0.5 m wide at the base), display upward-pointing apices, and have subvertical, northeastward-plunging axes that crosscut regional host-rock fabrics. Key characteristics of superficially similar, but non-shock-generated conical and striated features are inconsistent with the properties of the Santa Fe cones. In thin section, sub-millimeter-scale, dark, semi-opaque to isotropic veneers on cone surfaces and veinlets within cone interiors closely resemble previously described shock-induced melt features. Microscopic grain alteration, restricted generally to within 1 mm of the cone surfaces, includes random fractures, fluid micro-inclusions, sericite replacement in feldspar, rare kink bands in mica, optical mosaicism, and decorated planar fractures (PFs) and planar deformation features (PDFs) in quartz. The PFs and PDFs are dominated by a basal (0001) crystallographic orientation, which indicate a peak shock pressure of ~5–10 GPa that is consistent with shatter cone formation. Regional structural and exhumation models, together with anomalous breccia units that overlie and crosscut the shatter cone-bearing rocks, may provide additional age constraints for the impact event. The observed shatter cone outcrop area suggests that the minimum final crater diameter of the Santa Fe impact structure was ~6–13 km.

1. Introduction

Of the approximately 174 presently confirmed Earth impact craters and structures, only five are located in the western United States, a number that is statistically low given the crater density recorded elsewhere on the North American continent (http://web.eps.utk.edu/ifsg.htm; http://www.unb.ca/passc/ImpactDatabase/index.html). The active tectonic history of the western United States, which is characterized by widespread episodes of compressional and extensional deformation, erosion, sedimentation, and volcanism (Burchfiel et al., 1992), especially hampers the preservation of impact structures. In such an active tectonic regime, the likelihood of complete crater preservation decreases dramatically with increasing age. Known terrestrial impact events in these active settings are evidenced by buried, partially eroded, or tectonically dismembered craters or by isolated occurrences of proximal to distal impactite deposits that may or may not be linked to a preserved source crater. With the exception of the young and well-preserved Barringer crater, Arizona, four of the five confirmed impact events in the United States west of the Interior Plains province are evidenced by craters that are buried (Cloud Creek, Wyoming — Stone and Therriault, 2003), highly eroded (Upheaval Dome, Utah — e.g., Kriens et al., 1999; Buchner and Kenkmann, 2008), or tectonically dismembered (Beaverhead, Montana — Hargraves et al., 1990, 1994; and Alamo, Nevada — e.g., Warme and Kuehner, 1998; Morrow et al., 2005; Pinto and Warme, 2008).

During fieldwork conducted in 2005, one of us (McElvain) discovered anomalous, large, nested cone-like structures within road cut and natural exposures of tectonically complex Paleoproterozoic intrusive igneous and metamorphic rocks in the southern Sangre de Cristo Mountains northeast of Santa Fe, New Mexico, USA (Figs. 1, 2). Subsequent

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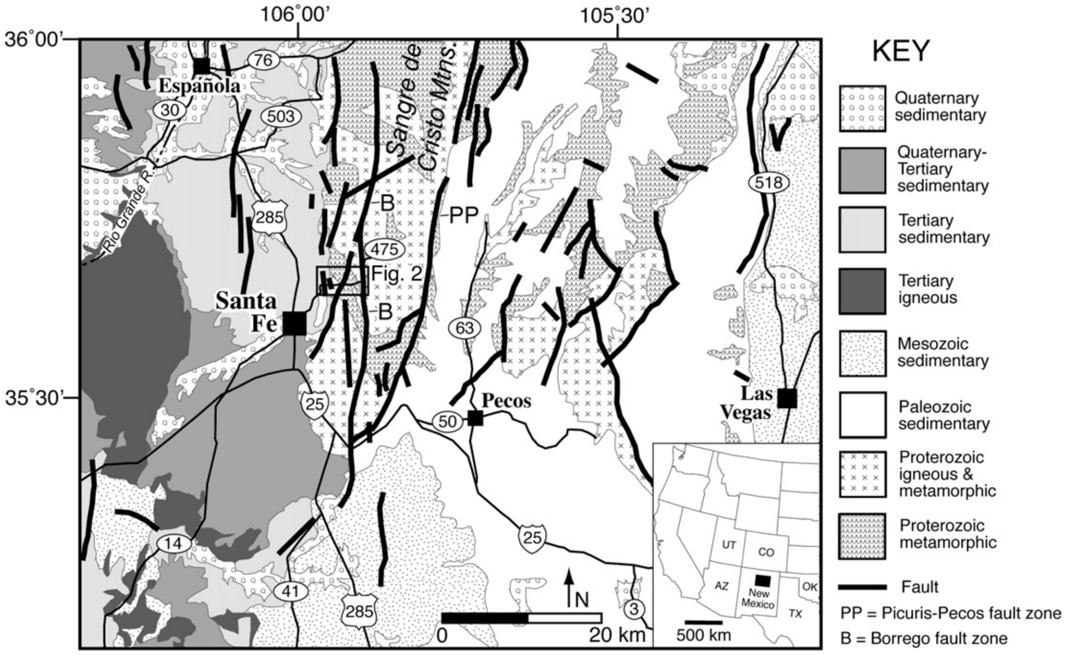

Fig. 1. Locality and generalized geologic map of study region, showing area depicted in Fig. 2 (rectangle). Major highways and cities are shown. Key defines major lithologic types and corresponding map patterns. Geology is simplified from Geologic Map of New Mexico (New Mexico Bureau of Geology and Mineral Resources Staff, 2003).

detailed mapping, measurement, and petrographic analysis of the cone structures, including work conducted as part of a graduate student research project (Fackelman, 2006), strongly indicates that these structures are shatter cones from a previously unrecognized, but highly eroded or tectonically dismembered terrestrial impact structure (Fackelman et al., 2006; McElvain et al., 2006; Fackelman et al., 2007; Newsom et al., 2007). In the region, unusual, structurally complex breccias and megabreccias overlie and crosscut the Precambrian crystalline rocks containing the shatter cones. These anomalous breccias are currently under study (e.g., McElvain et al., 2006; Newsom et al., 2007) to further establish a possible genetic link with the impact event. In this paper, we provide initial results documenting the occurrence and morphology of the shatter cones and the shock-related alteration and micro-deformation within the shatter cone-bearing rocks.

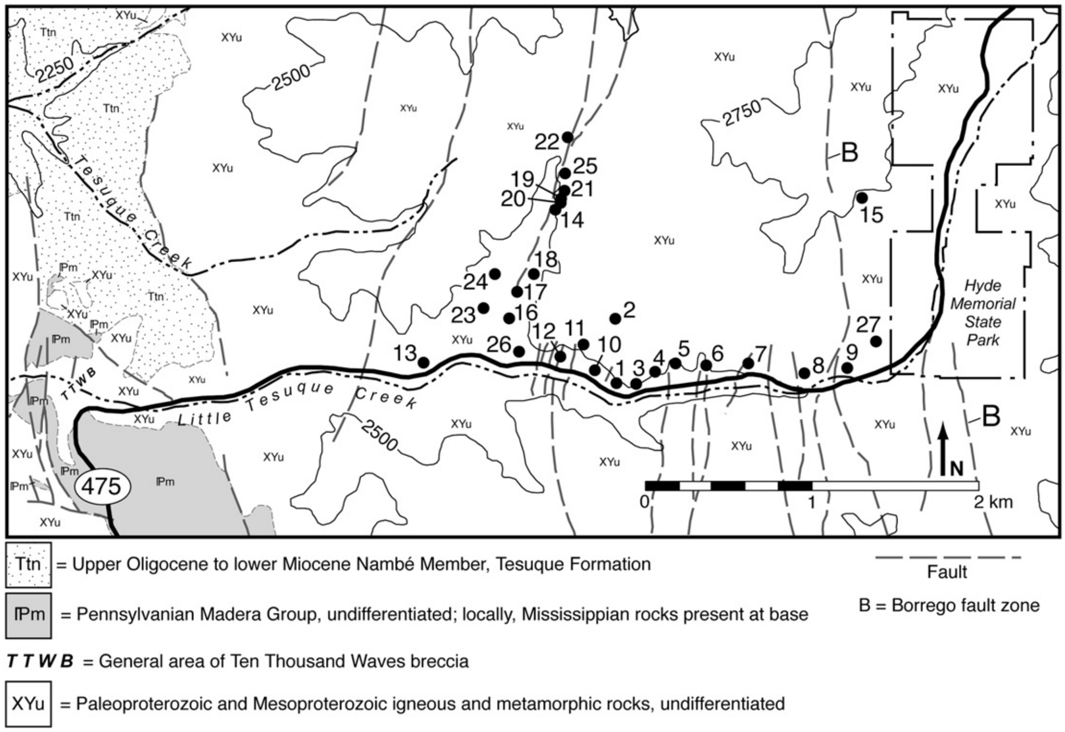

Fig. 2. Map of study area, showing shatter cone localities (numbers; see also Appendix A), generalized topography, generalized bedrock geology, and New Mexico State Highway 475. Topographic contours are meters above sea level; contour interval is 250 m. General outcrop area of Ten Thousand Waves breccia (McElvain et al., 2006; Newsom et al., 2007) is also shown. Geologic data after Bauer et al. (1997) and Read et al. (2000).

2. Geologic setting

2.1. Introduction

The shatter cones occur ~8 km northeast of Santa Fe, within tectonically complex Proterozoic crystalline rocks exposed in the Santa Fe Range, a southwestward extension of the southern Sangre de Cristo Mountains (Figs. 1, 2). The cones are best exposed along the north side of Little Tesuque Creek, which flows west through one of several narrow, rugged, east-west-trending canyons that drain the western side of the Santa Fe Range. The elevation of the study area varies from approximately 2400 m to 2750 m above sea level. No obvious geomorphic evidence of a circular, crater-like feature is preserved at or surrounding the shatter cone exposures.

The north-south-trending Sangre de Cristo Mountains, which are part of the larger Southern Rocky Mountains physiographic province, extend about 360 km from south-central Colorado in the north to a point several kilometers southeast of Santa Fe at the south end. The southern Sangre de Cristo Mountains are bounded to the west by the north-south-trending Rio Grande rift zone and to the east by the generally low-relief High Plains physiographic province. To the west of the study area, rock sequences are dominated by Cenozoic volcanic and siliciclastic sedimentary units deposited within the Española basin (Fig. 1; Read et al., 2000), a depocenter that developed in response to Rio Grande rifting and extension. The eastern side of the study area is bordered by the Borrego–Picuris–Pecos fault system (Figs. 1, 2), which is an important crustal shear zone that has accommodated a net right-lateral offset of ~40 km since about 1.4 Ga (Karlstrom and Daniel, 1993; Cather et al., 2006).

The earliest major tectonic event affecting Proterozoic rocks in the region was the suturing of the 1.76–1.72 Ga Yavapai and 1.7–1.6 Ga Mazatzal crustal terranes during the ~1.65 Ga Mazatzal orogeny (Karlstrom et al., 2004). At least seven important post-1.65 Ga tectonic events have been identified: (1) an ~1.45–1.35 Ga magmatic and orogenic event, (2) the ~1.1 Ga Grenville orogeny, (3) the ~0.7 Ga rifting of western Rodinia, (4) Cambrian extension and magmatism associated with rifting in the southern Oklahoma aulacogen, (5) the late Paleozoic Ancestral Rocky Mountain orogeny, (6) the Late Cretaceous–Eocene Laramide orogeny, and (7) Neogene extension related to the Rio Grande rift (Cather et al., 2006). Regional exhumation and exposure of the Proterozoic crystalline basement were largely complete by the middle Paleozoic, when widespread Mississippian and Pennsylvanian marine sediments were deposited across the area. The intervening, sub-Mississippian Great Unconformity evidences an ~1.3-b.y.-long hiatus in the geologic record.

2.2. Geology of shatter cone-bearing rock units

The oldest rocks preserved in the study area (Fig. 2) are ~1.7–1.8 Ga metavolcanic and metasedimentary supracrustal rocks, including amphibolite, biotite and muscovite schist, quartzofeldspathic schist, and quartzite (Bauer et al., 1997; Read et al., 2000). The protoliths of these Paleoproterozoic units were rhyolites, basalts, and siliciclastic sediments deposited into a back-arc basin formed along the southern margin of the Yavapai crustal block. Initial deformation and metamorphism of the sediments began at ~1.65 Ga during the Mazatzal orogeny (Karlstrom et al., 2004). It was estimated that peak burial temperature and pressure conditions of 500–550 °C and 0.35–0.4 GPa, respectively, were reached during the ~1.45–1.35 Ga magmatic and orogenic event (Williams et al., 1999; Karlstrom et al., 2004). In this area, igneous intrusions consisting of diorite, granodiorite, mica granite, granitoid, and pegmatite were emplaced periodically from the late Paleoproterozoic to the Mesoproterozoic (Bauer et al., 1997).

The lowest, relatively undeformed Paleozoic shallow-marine sedimentary rocks that unconformably overlie Proterozoic crystalline rocks in this area consist of isolated outcrops of Mississippian quartzite and limestone and widespread Pennsylvanian limestone, calcareous siltstone, shale, and minor sandstone of the Madera Group (Read et al., 2000). Approximately 2 km west of the shatter cone area, an anomalous, ~75-m-thick Proterozoic lithic-clast breccia is locally present (McElvain et al., 2006). The breccia, which is informally termed the “Ten Thousand Waves breccia” (TTWB, Fig. 2), overlies the crystalline basement, is post-Proterozoic to pre-Pennsylvanian in age, and may be intercalated with Mississippian rocks (A.S. Read, oral commun., 2006; McElvain et al., 2006).

The shatter cones occur in both Paleoproterozoic intrusive igneous and metamorphic rocks (Fig. 2), although they are more abundant and well developed in the former. Foliation and banding, which are present in both rock types, generally dips to the southwest at 40–55° (Bauer et al., 1997; Fackelman, 2006). The intrusive igneous rock is dominated by an orange to pink to red, fine- to medium-grained, equigranular granitoid that commonly contains layers and lenses of supracrustal metamorphic rocks and minor granitic pegmatite (Bauer et al., 1997). Biotite, potassium and plagioclase feldspar, quartz, muscovite, and iron oxide minerals are common components of the granitoid. It is weakly foliated to strongly foliated and banded; where banded, it approaches a gneissic granitoid in texture (Bauer et al., 1997).

The cone-bearing supracrustal metamorphic rocks are heterolithic and interlayered, and include a quartzofeldspathic unit and amphibolite. Within the quartzofeldspathic unit are intercalated quartz-rich, fine-grained schist, quartzite, and quartz–feldspar–muscovite gneiss. Laminations and layering within the quartzite preserve probable primary sedimentary structures, evidencing a quartz sandstone protolith. The amphibolite is black to green and fine- to coarse-grained, containing common blue-green hornblende, plagioclase feldspar, quartz, and sphene, with variable amounts of epidote, garnet, biotite, and chlorite after biotite (Bauer et al., 1997).

3. Shatter cone occurrence and morphology

3.1. Introduction

As one of the key physical indicators of terrestrial impact events, shatter cones are the only meso- to macro-scale feature that gives uniquely diagnostic evidence of hypervelocity impact (French and Short, 1968; French, 1998). These conical features, composed of outward curving, horsetail-like striated surfaces, have been described for over 100 years from impact sites around the world, although their significance as unique indicators of shock deformation was not widely accepted by the geoscience community until the 1960's (French, 1998). Examples of early studies that noted the presence of shatter cone-like features include Branco and Fraas (1905; Steinheim basin, the “type locality” of shatter cones), King (1930; Sierra Madera structure), Shrock and Malott (1933; Kentland structure), Bucher (1936; Wells Creek basin and Serpent Mound structure), Wilson and Born (1936; Flynn Creek structure), Hendriks (1954; Crooked Creek structure), Dietz (1961, 1964, 1968; Vredefort dome, Sudbury basin, and Manicouagan structure, respectively), Hargraves (1961, Vredefort dome), Dence (1964; Clearwater Lake structures), and Crook and Cook (1966, Gosses Bluff structure). All of these twelve localities have since been verified through additional studies to be terrestrial impact structures (see, e.g., references cited at: http://www.unb.ca/passc/ImpactDatabase/index.html).

Subsequent reports have used the presence of shatter cones as uniquely diagnostic evidence for an impact event (e.g., Hargraves et al., 1990, 1994; Hargraves and White, 1996; Pirajno et al., 2003; Macdonald et al., 2005; Milton and Macdonald, 2005) or have examined in more detail the still not fully understood processes and mechanisms of shatter cone formation (e.g., Gash, 1971; Gay, 1976; Milton, 1977; Roddy and Davis, 1977; Gay et al., 1978; Martini, 1991; Gibson and Spray, 1998; Nicolaysen and Reimold, 1999; Sagy et al., 2002; Baratoux and Melosh, 2003; Sagy et al., 2004; Wieland et al., 2006).

Shatter cones consist of "distinctly striated conical fragment[s] of rock ranging in length from less than a centimeter to several meters, along which fracturing has occurred; generally found in nested or composite groups" (Bates and Jackson, 1987, p. 607). Shatter cones occur in all types of shock-metamorphosed rocks, although they are favored in fine-grained and homogenous lithologies (e.g., Dietz, 1961; Manton, 1965; Dietz, 1968; Wieland et al., 2006). As documented by Wieland et al. (2006), however, the presence of small-scale pre-impact heterogeneities within a given lithology can increase the density of cone formation and will affect the resulting cone morphologies. Based on work at Vredefort dome, Manton (1965), Nicolaysen and Reimold (1999), and Wieland et al. (2006) further recognized that shatter cones are composed of intersecting sets of curviplanar fractures (multiply striated joint sets, MSJS), which can contain on their surfaces a large variety of striae types including clustered, fan shaped, or complexly curved. Recent modeling of shatter cone formation suggests that the cones are tensile features intimately associated with MSJS, which form in the target rock immediately after passage of the impact shock wave front (Baratoux and Melosh, 2003; Wieland et al., 2006).

3.2. Shatter cone occurrence

In this study, the shatter cones occur within an ~5.5 km^2 area north of Highway 475, between Santa Fe and Hyde Memorial State Park (Figs. 2–6). Although they are best exposed and developed

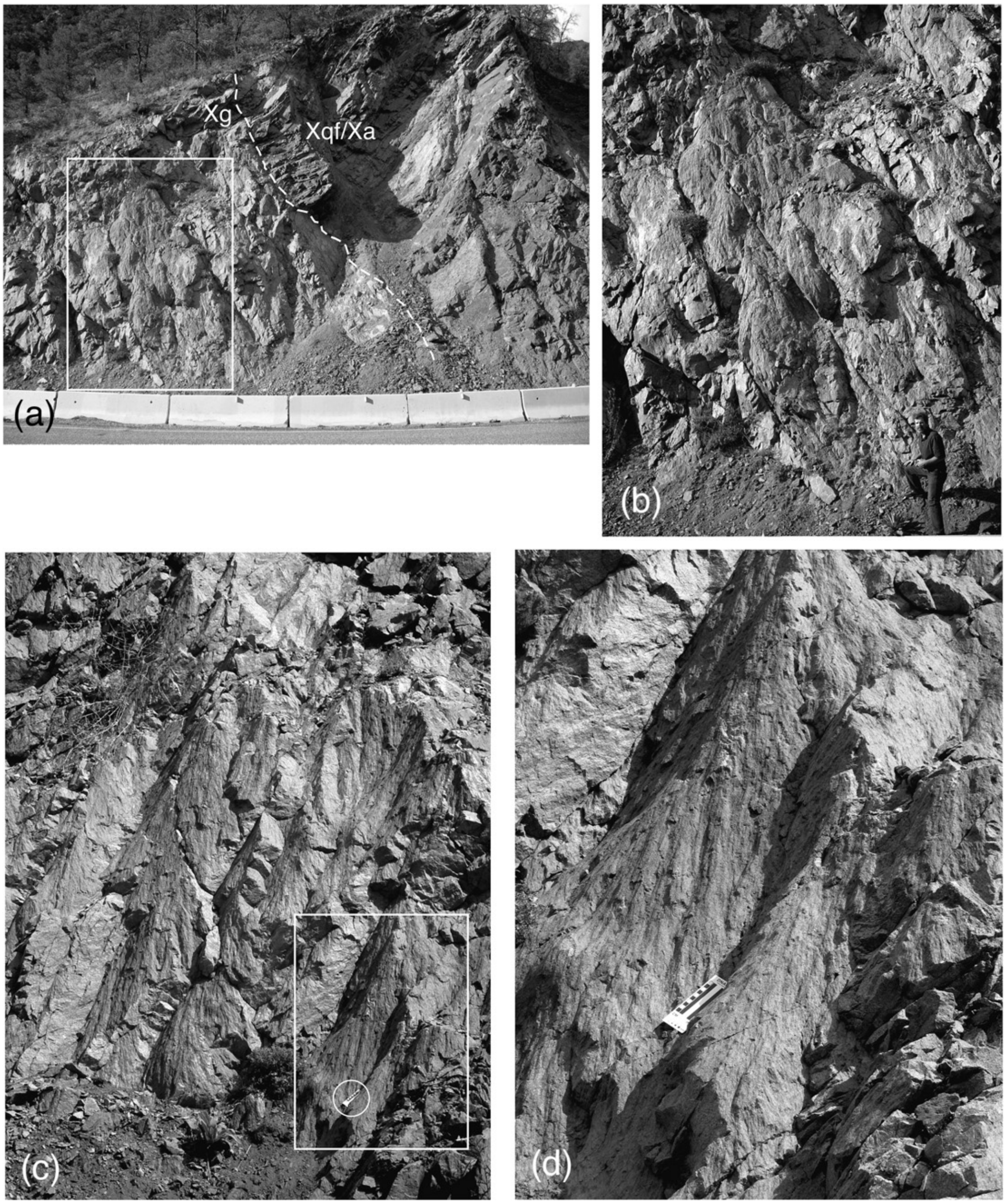

Fig. 3. Outcrop photographs of south-facing road cut exposure along Highway 475. a) Contact between shatter cone-bearing Paleoproterozoic granitoid (Xg) and quartzofeldspathic and amphibole-rich supracrustal rocks (Xqf and Xa, respectively). Width of view is approximately 50 m. Locality 1 (Fig. 2); inset shows position of b. Geology is after Bauer et al. (1997). b) Western end of exposure shown in a, showing nested series of shatter cones characterized by meter-scale, curviplanar striated surfaces developed in fine- to medium-grained granitoid. Cones are crosscut and partly truncated by local east-dipping joint set. Person for scale. c) Nested series of meter-scale shatter cones developed in fine- to medium-grained Paleoproterozoic granitoid. Scale (circled) is 10 cm long. Locality 3 (Fig. 2); inset shows position of d. d) Well-developed, nested, sub-conical to curviplanar shatter cones displaying common multiple sets of striated surfaces with curved striae that bifurcate downward from cone apices, forming a horsetail-like pattern. Scale is 10 cm long.

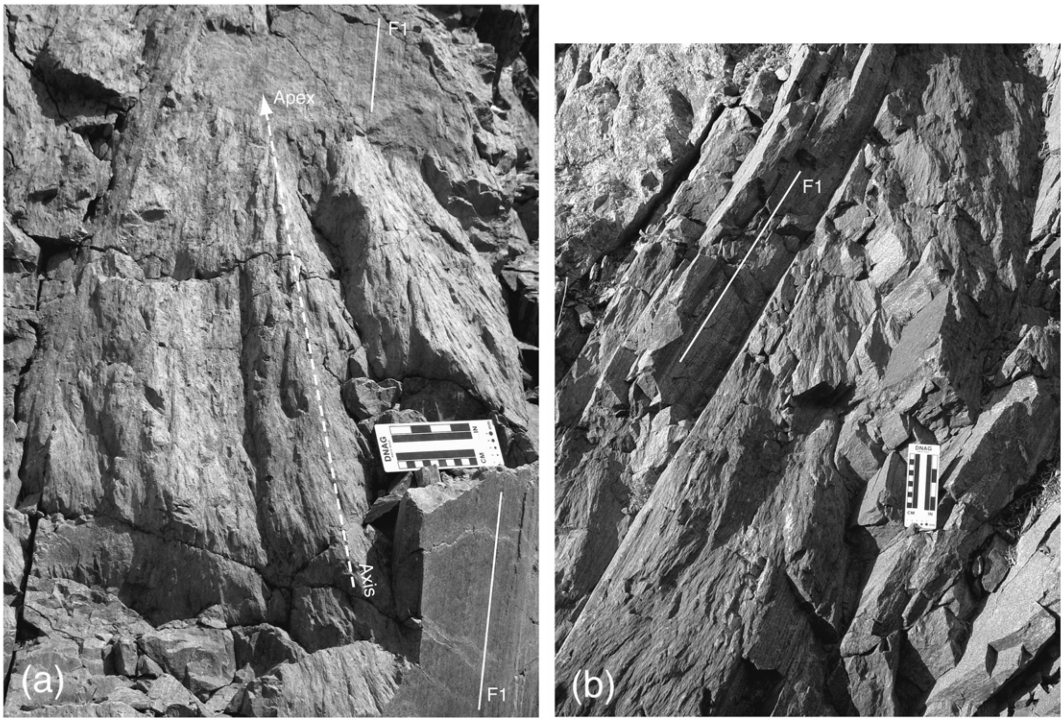

Fig. 4. Outcrop photographs of shatter cones developed in Paleoproterozoic supracrustal metamorphic rocks exposed along Highway 475, east end of Locality 1 (Fig. 2), showing examples of cone axes that crosscut metamorphic fabrics. a) Subvertically oriented cones cutting across primary foliation (F1) or relict bedding in fine-grained, quartz-rich schist and quartzite. Primary foliation dips steeply to the southwest. One cone axis and apex are labeled. Scale is 10 cm long. b) Poorly developed, subvertically oriented, striated curviplanar surfaces that crosscut primary foliation (F1) in fine-grained, quartz-rich schist. Scale is 10 cm long.

directly north of the highway in natural exposures that have been enlarged by road construction (e.g., Figs. 3–5), good examples also occur in undisturbed natural outcrops up to ~1.5 km north of the highway (Figs. 2, 6), eliminating any possible link between road construction and their genesis. Although not plotted on Fig. 2, several small shatter cones were also found in float rock to the south of Highway 475 (T.H. McElvain, unpub. data, 2005), demonstrating a potentially larger area of occurrence. However, field reconnaissance directly around the known area of shatter cone occurrences has not revealed additional in situ exposures (Fackelman, 2006). As noted above, the cones occur exclusively in Paleoproterozoic intrusive igneous and metamorphic rocks, which are unconformably overlain by middle Paleozoic strata exposed ~2 km to the west (Fig. 2).

Fig. 5. Outcrop photograph of large, well-developed, complexly striated shatter cone surface developed within fine- to medium-grained Paleoproterozoic amphibolite, Highway 475, west end of Locality 3 (Fig. 2). Scale is 10 cm long.

3.3. Shatter cone morphology

The shatter cones observed in this study are characterized by nested and complexly intersecting series of sub-conical, curviplanar, and flat joint surfaces bearing abundant curved and bifurcating

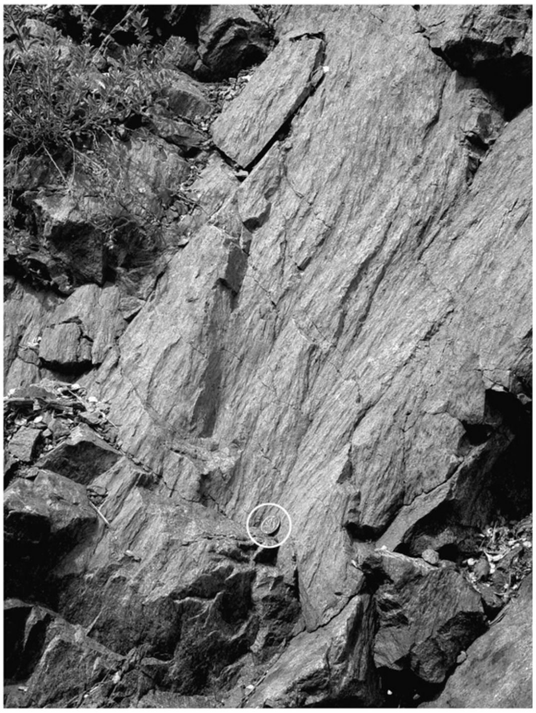

Fig. 6. Outcrop photograph of shatter cones developed as curviplanar, downward-widening striated surfaces within medium-grained Paleoproterozoic granitoid, Locality 18 (Fig. 2), exposed ~0.6 km north of Highway 475. Coin (circled) is 2.5 cm in diameter.

striations (Figs. 3–7), which strongly resemble the MSJS described by Nicolaysen and Reimold (1999) and Wieland et al. (2006) at Vredefort dome. As these authors noted, complete three-dimensional cones are rare, a phenomenon also observed in this study. Where three-dimensional cones are found, the cone surface is defined by flat to curviplanar, complexly striated surfaces (Fig. 7a) that are often oriented roughly tangential to the cone axis. The apical angles of these poorly developed three-dimensional cones are about 90°.

The shatter cones are developed as: (1) intersecting, variably oriented, flat to curviplanar striated surfaces (Fig. 7a) and (2) larger, well-organized, nested, sub-conical and curviplanar striae-bearing surfaces that share a common main axis and apex, and show striations that are developed in a roughly radial pattern from the main axis (Figs. 3d, 4a; cf. Wieland et al., 2006). Preliminary measurements of variably developed "striation angles" or "V angles" (Sagy et al., 2002, 2004; Wieland et al., 2006) on the shatter cone surfaces, which are subordinate inverted V-shaped striations developed on larger cone faces, indicate common striation angles of ~38–60°, although several larger angles were noted (Fackelman, 2006). The striation angles measured here are in part wider than those reported from Vredefort, which are generally <50° (Sagy et al., 2002, 2004; Wieland et al., 2006). Ongoing work is evaluating this difference in more detail.

The shatter cones are best developed in the most homogenous rock types, such as granitoid and amphibolite, where they can reach up to ~2 m in length and ~0.5 m in width at the base (Figs. 3, 5). These rock types, although homogeneous and massive at the outcrop scale, often show common meso- to micro-scale grain-size variations and textural heterogeneities. In foliated and banded rock types, such as the schist, quartzite, and gneiss, the cones are generally smaller and less well developed, with axis lengths reaching up to ~1 m and widths up to ~0.3 m at the base (Fig. 4). The largest cones are present in the road cut outcrops directly north of Highway 475 (Fig. 2), although relatively well-developed, decimeter-scale examples are also found in undisturbed, naturally exposed granitoid exposures (Fig. 6) north of the highway (Fig. 2). This distribution unequivocally indicates that the shatter cones are clearly penetrative structures, extending well into the outcrop.

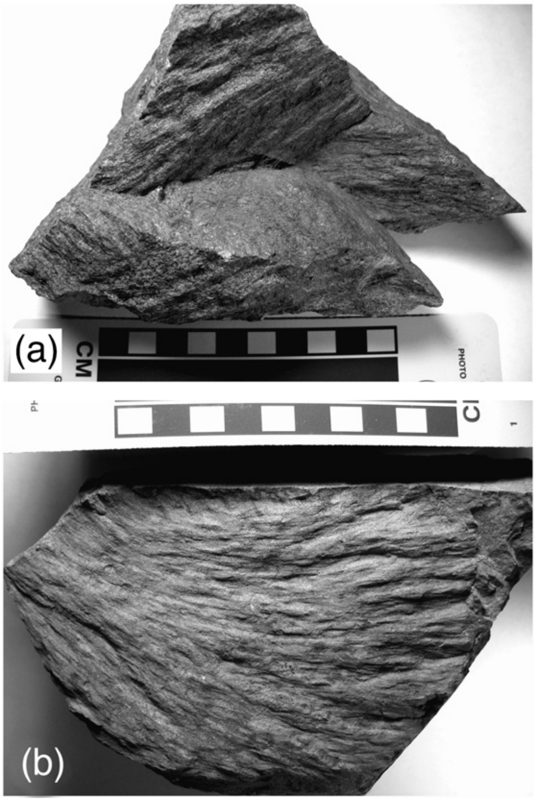

Fig. 7. Laboratory photographs of shatter cones. a) Medium-grained granitoid sample, showing complex intersection of at least three sets of striated, curviplanar surfaces with variably oriented axis directions, Locality 3 (Fig. 2). Scale is 10 cm long. b) Fine-grained quartz-rich schist sample, showing single curved striation-bearing surface, Locality 1 (Fig. 2). Scale is 10 cm long.

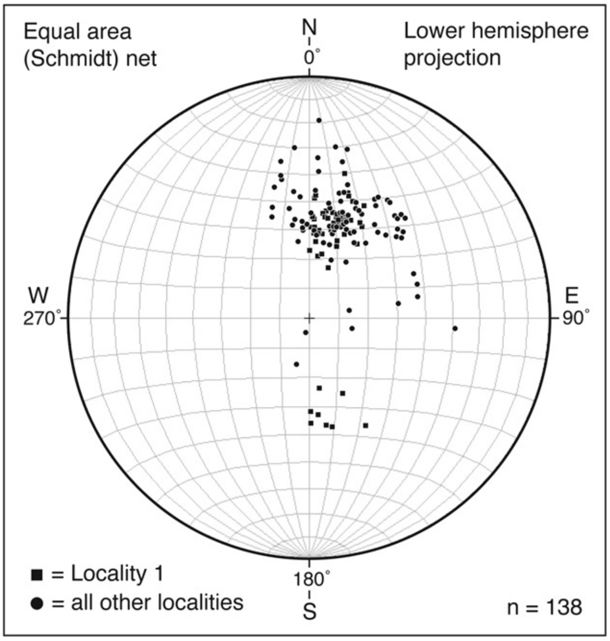

Fig. 8. Lower hemisphere, equal area (Schmidt) stereonet projection showing orientations of all primary shatter cone axes ($n=138$), Santa Fe impact structure. Locality 1 axes ($n=56$) are shown by black squares; axes of other localities combined ($n=82$) are shown by black circles. Cone apices project upward away from the plane of the stereonet. Axis orientations, consisting of a bearing direction and plunge angle, were measured with Brunton compass; measurement accuracy is ±5° for both parameters. Data from Appendix A.

The majority of the larger shatter cone apices point upward, with a subvertical orientation of cone axes. Measurements of cone axis orientations, based on the bearing direction and plunge angle of the primary, or master, cone axis determined with a Brunton compass, show that the axes clearly crosscut the trends of regional metamorphic foliation and banding and local jointing (Figs. 3, 4). Foliation and banding generally dips to the southwest at 40–55° (Bauer et al., 1997; Fackelman, 2006). In contrast, a stereonet plot of the trend of 138 shatter cones axes (Fig. 8) demonstrates that the average axis orientation, which bears N18°E and plunges 56° away from cone apices, is oblique to nearly perpendicular to the regional metamorphic fabric, a property that is also readily observed in outcrop (Fig. 4). As shown in Fig. 8, the majority of the axes plot into a relatively tight pattern with northeastward-directed plunges. Most of the outliers, showing southward- to southeastward-directed plunges, were measured at Locality 1, which also yielded numerous plunges to the northeast (Fig. 8). This difference may be due to slight post-impact rotation across minor faults that crosscut the locality, or by differences in the primary orientations of the shatter cone axes at this locality. Taken as a whole, however, the cone axes display an unexpectedly tight cluster of orientations that are subvertically oriented; given the complex tectonic history of the study area, this observation may be significant in further refining the relative age of the event.

The macroscopic physical properties of the Santa Fe cones compare closely with documented shatter cones at other crystalline-target impact sites, including Vredefort (Hargraves, 1961; Manton, 1965; Dietz, 1968; Nicolaysen and Reimold, 1999; Wieland et al., 2006), Clearwater Lake West (Dence, 1964), Sudbury (Dietz, 1964; French, 1968, 1972, 1998), Manicouagan (Dietz, 1968), Slate Islands (Halls and

Grieve, 1976; Dressler et al., 1998, 1999), and Beaverhead (Hargraves et al., 1990, 1994). The features described in this study occur exclusively within Paleoproterozoic intrusive igneous and metamorphic host rocks, thus excluding a possible origin as either sedimentary cone-in-cone structures (Dietz, 1968; French, 1998; Lugli et al., 2005) or as striated cones such as those reported from Neogene felsic volcanic-vent rocks exposed several kilometers west of Albuquerque, New Mexico (Elston and Lambert, 1965). The sub-conical and curviplanar surfaces of the cones, the complex, non-parallel striae that bifurcate away from the cone axes in horsetail-like patterns, and the of lack evidence for micro-steps or aligned slickenfibers on the cone surfaces all exclude a fault slickenside origin for these features (Dietz, 1968; French, 1998; Passchier and Trouw, 2005). Further, the occurrence of the cones as penetrative structures within recently exposed rocks along road cuts eliminates an alternate possible origin as near-surface weathering or wind ablation features (Elston et al., 1968).

4. Microscopic shock features

4.1. Introduction

An important property of many previously documented shatter cones, and one that further establishes their link to shock-metamorphic processes, is the presence of microscopic shock-alteration features located generally within ~2 mm of cone surfaces and MSJS intersections (cf., Hargraves and White, 1996; Nicolaysen and Reimold, 1999). These shock-related features include glassy particles and microspherules along cones surfaces (e.g., Gay, 1976; Gay et al., 1978); common glassy melt patches or veneers, generally <0.5 mm thick, developed on or parallel to the surfaces of cones and MSJS (e.g., Hargraves and White, 1996; Gibson and Spray, 1998; Nicolaysen and Reimold, 1999; Wieland et al., 2006); micro-structural damage consisting of intergranular cracks developed subparallel to the surfaces of cones and MSJS (e.g., Nicolaysen and Reimold, 1999); and grain micro-deformation features such as random fractures, kink bands, planar fractures (PFs), and planar deformation features (PDFs) (e.g., Lilly, 1981; Hargraves and White, 1996; French, 1998; Nicolaysen and Reimold, 1999).

Generally, in this setting the quartz PDFs are dominated by single sets of decorated lamellae oriented parallel to the basal pinacoid (0001) (Carter, 1965), which probably represent annealed, shock-specific Brazil twins (Leroux et al., 1994; Joreau et al., 1996). Based on laboratory single-crystal shock experiments and analyses of naturally shocked crystalline target rocks, the occurrence of basal PDFs in quartz in the absence of higher index plane sets indicates peak shock pressures of ~5–10 GPa (Stöffler and Langenhorst, 1994). This range is within the broadly constrained pressure regime of ~2–30 GPa for shatter cone formation (French, 1998).

4.2. Probable melt features

Analysis of petrographic thin sections cut perpendicular to the outer margins of several shatter cones has identified thin rinds or patches, generally <50 µm thick, of cryptocrystalline, dark-green to dark-brown, semi-opaque to rarely isotropic material that coats the shatter cone surfaces (Fig. 9). The dark material also forms apparently discontinuous patches and veinlets that occur parallel to, and sometimes branch from, the coatings on the outer cone surfaces. The majority of the dark material occurs within ~1 mm of the cone margins, although veinlets, generally oriented parallel to subparallel to the outer surface, occur deeper within the interior of the cones. The nature and occurrence of this dark material is consistent with previously documented microscopic glass or melt features present along the surfaces of shatter cones from Vredefort dome (Gay et al., 1978; Nicolaysen and Reimold, 1999) and the Beaverhead (Hargraves and White, 1996) and Sudbury (Gibson and Spray, 1998) structures. Dark veinlets in the interior of the cones may represent melt developed along MSJS, a phenomenon documented at Vredefort dome by Nicolaysen and Reimold (1999). Additional chemical and microtextural analyses of the probable melt are currently being conducted.

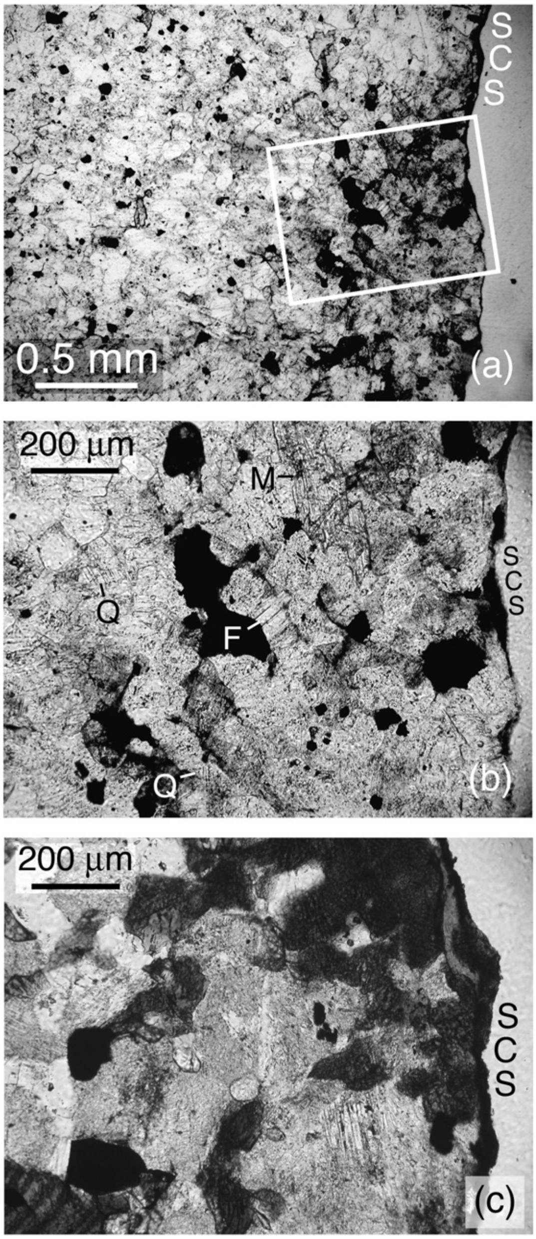

Fig. 9. Thin-section photomicrographs perpendicular to outer surface of shatter cones, showing shock-alteration features at and near cone surface. a) Low-magnification view across shatter cone surface (SCS) developed in fine-grained, quartz-rich schist. Note steep gradient, over a distance of <2 mm, in degree of alteration from highly altered cone surface at right to relatively unaltered sample interior to left. Shock-alteration features are discussed in text. Inset shows area of b. Sample WUR-SF2, Locality 1 (Fig. 2), plane-polarized light. b) Higher magnification view of sample shown in a, showing details of micro-alteration fabric near the shatter cone surface (SCS), located at right edge of image. Interpreted shock-alteration features include a dark, thin, irregular, semi-opaque to isotropic rind of probable melt on cone surface; common micro-fracturing in quartz (Q), feldspar (F), and mica (M), which shows deformation or possible kink bands; common fluid micro-inclusions within grains; common sericite-altered feldspar; and rare planar microstructures in quartz (labeled grains). Plane-polarized light. c) Fine- to medium-grained amphibolite, showing interpreted shock alteration at and near shatter cone surface (SCS), including patchy, semi-opaque to isotropic rind of probable melt on cone surface; pervasive grain micro-fracturing; common fluid inclusions within grains; and common sericite-altered feldspar. Sample WUR–SF1, Locality 3 (Fig. 2), plane-polarized light.

To date, no glassy microspherules, another common feature documented on shatter cone surfaces at Vredefort, have been found. Other alteration present beneath the cone surfaces and directly next to dark veinlets in the cone interiors (Fig. 9) includes common grain micro-fractures; common fluid micro-inclusions and inclusion patches within mineral grains, which appear in part "toasted" (cf., Whitehead et al., 2002); common sericite replacement within feldspar grains; rare kink bands in mica; rare blocky optical extinction patterns or grain mosaicism; and rare planar microstructures in quartz, discussed below.

4.3. Planar microstructures in quartz

In thin section, rare planar microstructures are present in quartz grains within ~1 mm of the cone surfaces (Fig. 9b) and adjacent to dark veinlets in the cone interiors. The planar microstructures, which occur as only one set of parallel lamellae per grain, are highly decorated with fluid micro-inclusions, are ~1–3 µm thick, and are spaced ~2–15 µm apart (Fig. 10). Based on their spacing, the planar microstructures may represent either PFs or PDFs (Stöffler and Langenhorst, 1994; French, 1998). Universal stage microscope indexing of 20 planar microstructure-bearing quartz grains showed that 18 of the grains contain sets with a basal (0001) crystallographic orientation (Figs. 10a–10c). The other two grains contained PFs with higher index set orientations (Fig. 10d). Optical mosaicism is a common property of the planar microstructure-bearing quartz grains.

Consistent with quartz planar microstructures that have been previously documented from other shatter cone localities (cf., Carter, 1965; Lilly, 1981; Hargraves and White, 1996; French, 1998; Wieland et al., 2006), the basal lamellae documented in this study may represent annealed, micro-inclusion-defined, shock-specific Brazil twins (Leroux et al., 1994; Joreau et al., 1996). Such shock-generated PFs and PDFs would indicate peak shock pressures of ~5–10 GPa (Stöffler and Langenhorst, 1994; French, 1998).

5. Summary and discussion

5.1. Summary

Field mapping, morphologic description, and petrographic analysis of unusual, sub-conical, complexly striated surfaces developed in Paleoproterozoic crystalline rocks northeast of Santa Fe all indicate the occurrence of previously unrecognized, impact-generated shatter cones. Specific important observations regarding these features include:

1. The shatter cones, which are up to 2 m long and 0.5 m wide at the base, occur in both intrusive igneous and supracrustal metamorphic rocks exposed in an area >5 km^2. The largest cones are developed in homogeneous and massive rock types such as granitoid and amphibolite.
2. The shatter cones are composed of nested, sub-conical, curviplanar, and flat joint surfaces bearing abundant curved and bifurcating striations that strongly resemble the MSJS previously described from shatter cones at Vredefort dome. Complete three-dimensional cones are rare.
3. Striations on the cone surfaces often form in sets of inverted, V-shaped structures that are subordinate to the main striated surfaces. This is consistent with shatter cones described at, e.g., Vredefort or Sudbury.

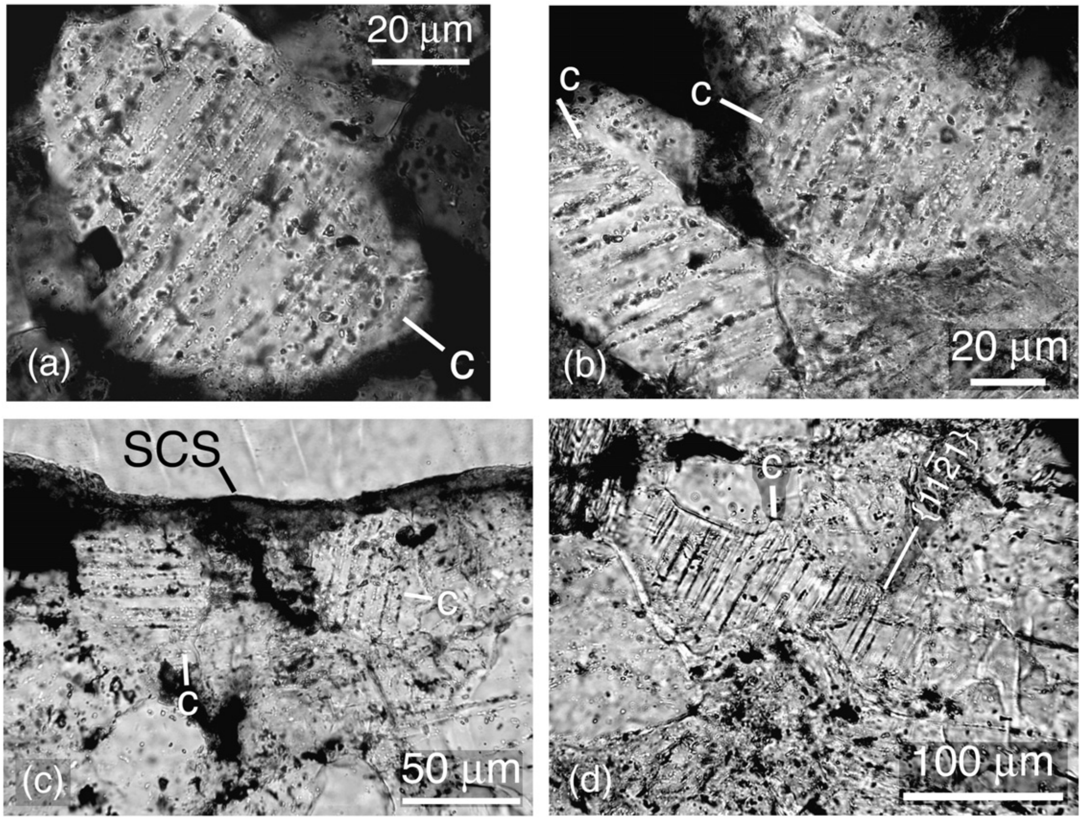

Fig. 10. Thin-section photomicrographs of decorated planar microstructures in quartz grains within shatter cone-bearing, fine-grained, quartz-rich schist. All images taken <2 mm from the cone surface. Sample WUR-SF2, Locality 1 (Fig. 2), plane-polarized light. a) Single set of decorated planar microstructures with basal (0001) orientation. The orientation and close spacing of planes, which are ~2–10 µm apart, indicate that these lamellae are annealed, inclusion-rich PDFs. b) Two grains that both contain one set each of highly decorated planar microstructures with (0001) orientation. Plane spacing is ~5–15 µm. These planes may represent PDFs or PFs. c) Another example of two planar microstructure-bearing grains at the shatter cone surface (SCS), showing thin rind and patchy inclusions of semi-opaque to isotropic melt material. As in b, the highly decorated planes may be PDFs or PFs. d) Grain with single set of decorated, but relatively well-defined PFs oriented parallel to $s\{11\bar{2}1\}$.

4. In most cases, the apices of the larger shatter cones point upward. The shatter cones axes, which are characterized by relatively consistent orientations, have an average bearing of N18°E and a plunge of 56°. These axes clearly crosscut the primary regional metamorphic foliation and banding, which generally dips to the southwest at 40–55°.
5. The occurrence of shatter cones in both artificially enlarged road cut outcrops and in undisturbed natural exposures up to 1.5 km north of the road clearly indicates not only that the structures cannot be the result road construction, but also that they are a penetrative rock fabric extending well below the surface.
6. Key characteristics of superficially similar, but non-shock-related features like cone-in-cone structures, fault slickensides, striated cones within vent-related volcanic rocks, and wind-ablation structures are inconsistent with the properties of the Santa Fe shatter cones.
7. Sub-millimeter-scale, dark, semi-opaque to isotropic veneers on cone surfaces and veinlets within cone interiors closely resemble shock-induced melt features previously described from shatter cones at other documented impact sites.
8. Other microscopic alteration of mineral grains, restricted generally to within 1 mm of the shatter cone surfaces and adjacent to veinlets in their interior, includes common random fractures, common fluid micro-inclusions, common sericite replacement in feldspar, rare kink bands in mica, rare optical mosaicism, and rare decorated PFs and PDFs in quartz. The PFs and PDFs are dominated by a basal (0001) crystallographic orientation, which is consistent with a peak shock pressure of ~5–10 GPa. This range is within the pressure regime of shatter cone formation.
9. Taken collectively, the data presented in this study give strong evidence of a previously unrecognized terrestrial impact structure, which is provisionally named the “Santa Fe impact structure”.

5.2. Discussion of impact age constraints

Based solely on the shatter cones that crosscut metamorphic foliation in the enclosing host rocks, the age of the impact event can only be definitely constrained as post-Paleoproterozoic. The U/Pb zircon radiometric age of quartz porphyry exposed ~10 km southeast of the study area, near the Picuris–Pecos fault zone (Fig. 1), is reported as 1660± 10 Ma (Renshaw, 1984, reported in Bauer et al., 1997), although the age relationship between this unit and rock units in the study area, e.g., the shatter cone-bearing granitoid, is uncertain. Thermochronologic models for the exhumation history of the southern Sangre de Cristo Mountains suggest that Proterozoic rocks exposed in the study region did not reach a purely brittle burial regime (i.e., <300 °C) until the onset of the Grenville orogeny or later, beginning at ~1.2–0.9 Ga (Erslev et al., 2004; Cather et al., 2006; Sanders et al., 2006). This suggests that the shatter cones could not have formed and been preserved prior to ~1.2 Ga, or the start of the late Mesoproterozoic.

Possibly also significant are the observations of the dominantly upward pointing shatter cone apices and the subvertical and tightly clustered orientations of their axes (Fig. 8). This might indicate that little or no major tectonic dismemberment or rotation, at least within the structural block(s) containing the shatter cones, has occurred since their formation. Such speculation might favor an even younger age for the impact event. However, the offset across the regionally significant shear zones (e.g., Borrego and Picuris–Pecos fault zones, Fig. 1) has been primarily strike slip with little documented dip slip motion (Cather et al., 2006); therefore, the effects of older (i.e., Proterozoic) post-impact tectonism may not necessarily have been recorded by the orientations of the shatter cone axes. In any case, no obvious geomorphic evidence of a circular, crater-like feature is preserved at or surrounding the shatter cone exposures. This indicates that a geologically recent impact was unlikely, and that crater is highly eroded, almost completely buried, or tectonically dismembered.

Ongoing work by colleagues at the University of New Mexico and the New Mexico Bureau of Geology and Mineral Resources is examining unusual, structurally complex breccias and megabreccias that overlie and crosscut the Proterozoic shatter cone-bearing rocks (McElvain et al., 2006; Newsom et al., 2007), in an effort to establish a genetic link with the impact event. This research includes analysis of the anomalous, post-Proterozoic to pre-Pennsylvanian Ten Thousand Waves breccia located west of the study area. If a link is confirmed, this may further constrain the age of the impact event to the early to middle Paleozoic, and possibly to within the Mississippian.

5.3. Discussion of crater size

In previously documented impact structures, shatter cones occur almost exclusively within the central uplift of complex impact craters (e.g., Dietz, 1968; Grieve, 1991; French, 1998). Therefore, the width of the shatter cone distribution area may serve as a rough proxy of the minimum diameter of the central uplift, which can be further scaled to the final apparent, or rim-to-rim, diameter of the crater (Melosh, 1989; Hargraves et al., 1994; Grieve and Therriault, 2004). In this study, shatter cones occur over an area with a minimum diameter of ~3 km. Applying the scaling formulas used by the authors cited above suggests that the Santa Fe impact structure had a minimum final crater diameter of ~6–13 km.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.03.033.

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