
Workshop Organizers: Shawn Wright (Planetary Science Institute), Aaron Cavosie (Curtin University, University of Wisconsin-Madison)

Table of Contents

Workshop on Sunday, July 23rd
   schedule              ii
   abstracts          iii - vi

Geologic History of the Santa Fe region  1

Road log for Sunday and Wednesday’s 2nd field trip
   “Shatter cones and breccias of the Santa Fe impact structure”  3

Field guide for Wednesday 1:30 field trip
   “Assembling Evidence of Impact at Highly Deformed Impact Craters: Detrital Shocked Minerals Grains”  11

References             21

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cover images: top left – shatter cone in metagranite with inset of a shatter cone in schist; top right – a breccia tower with person for scale; bottom right – pervasively fractured Proterozoic basement rocks with inset from a second location; bottom left – shock-twinned xenotime grain from a granite shatter cone (after Cavosie et al., 2016)
Sunday, July 23, 2017
WORKSHOP: RECOGNIZING THE CRITERIA FOR ANCIENT IMPACT STRUCTURES
9:30 a.m. La Fonda Hotel

This workshop focuses on the criteria for identifying ancient and/or degraded impact structures.

Chairs: Aaron Cavosie
        Shawn Wright

9:30 a.m. Reimold W. U. *
Recognition of Impact Structures: Part I. The Rock and Shock Record [#6048]
This contribution introduces the issues to be discussed at the “Recognizing the Criteria for Ancient Impact Structures” Workshop — focusing on shatter cones, geology and geophysics, and shock metamorphism.

10:15 a.m. Koeberl C. *
Recognition of Terrestrial Impact Structures, Part 2: Meteoritic Components, Shock Effects, and Other Characteristics [#6276]
Criteria for the identification of impact structures on Earth are reviewed.

11:00 a.m. Cavosie A. J. *
Shock Deformation at Degraded Impact Craters: The Santa Fe Structure [#6106]
Documenting evidence of shock deformation at degraded impact structures of any age is a challenge. This presentation reviews evidence of shock metamorphism at the Santa Fe impact structure as a case study for investigating degraded impact craters.

11:45 a.m. Field trip logistics

12:00 p.m. Break for lunch

1:30 p.m. Field Trip Departs from La Fonda
RECOGNITION OF IMPACT STRUCTURES: PART I. THE ROCK AND SHOCK RECORD.

W. U. Reimold, Museum für Naturkunde Berlin, Invalidenstrasse 43, 10115 Berlin, Germany; Humboldt Universität zu Berlin; Geochronology Laboratory, Universidade na Brasília, Brasilia, Brazil (uwe.reimold@mfn-berlin.de).

Introduction: This contribution introduces the issues to be debated at the “Recognizing the Criteria for Ancient Impact Structures” Workshop. The terrestrial impact record is seriously limited, in comparison to the records of other planetary bodies (e.g., Moon, Mercury); it is badly skewed towards relatively young structures. In addition, impact in the stratigraphic record is limited to a few Archean and Proterozoic spherule layers and a small number of Phanerozoic distal impact ejecta horizons; only 1 shocked quartz grain has been discovered to date from these layers. Generally, it seems that the easy-to-find impact structures or remnants thereof have already been identified, and that it will be much more difficult in future to add further to the record. The purpose of this workshop is to evaluate accepted (shatter cones, shock metamorphism, and physical or chemical traces of extraterrestrial projectiles) and possible further recognition criteria. The latter have been repeatedly invoked when the accepted impact evidence did not “work” (e.g., for Manitsoq, Greenland, or alleged craters in the Bajada del Diablo, Argentina – [1]). In all such cases, the alleged evidence failed to meet the standard – and the proposers failed to deliver proof that these alleged new criteria are the true outcome of shock (impact) deformation.

The rock record and geophysical anomalies: The literature is full of erroneous statements that geophysical anomalies or the presence of “pseudotachylite” represent evidence of impact. No morphological, geophysical, or breccia evidence represents bona fide evidence of impact! Ground- and/or laboratory proofing of any notion of impact remains required, and only then may shock metamorphic or chemical evidence be detected that can be regarded as essential and diagnostic. However, morphological and geophysical observations, perhaps coupled with regionally unique occurrences of lithic or melt (bearing) breccia, may provide first-order hints at impact – that then require detailed follow-up. If such observations are coupled with evidence of stratigraphic uplift and – in the case of very large structures/anomalies under consideration - elevated metamorphic gradient and/or occurrence of significant amounts of melt breccia, thorough exploration is warranted. This becomes problematic when only limited regional/local geological context is available, or an exotic terrain is studied. In those cases, detailed search for shock metamorphic indicators is then required.

Shatter cones (SC) are the only recognized meso- to macroscopic impact recognition criterion. In fact, they range in scale from mm size (recently recognized in MEMIN experiments) to 12 m (in the Slate Islands impact structure). They have been regarded as being typically formed in the low-shock regime (< 10 GPa) but in the literature there are reports that extend occurrence to 30-45 GPa. They were recognized in crater rim and central uplift settings. Long thought to occur mostly in fine-grained materials, recent work at Vredefort and Keurusselkä resulted in the description of well-developed SC in medium- to coarse-grained granitoids as well. A recent special issue of MAPS was dedicated to SC, also promoting some new ideas about their genesis [2]. While there is general agreement that SC formation is the result of interaction between a shock front and target-rock heterogeneities, especially pre-impact fractures, the process is still not resolved completely.

Recent advances in shock metamorphism: Quartz and zircon are the minerals of choice, in terms of being advantageous for the recognition of impact structures and tracing remnants of impact in the geological record. Recent work – also including EBSD SEM, cathodo-luminescence, and Raman studies - have contributed largely to a better understanding of shock processes at the grain scale. Shocked zircon has been traced in fluvial sediments for 1500 km from its source. The MEMIN research group studies not only confirmed that stishovite crystallizes from shock melt, but it also showed that porosity strongly enhances shock and associated thermal deformation, so that diaplectic glass and lechatelierite could be produced at < 10 GPa shock pressures [3]. Further work with weathering-resistant trace minerals may enlarge the arsenal for shock barometry and impact detection.

Finally, a general remark. Much about the impact process and the interaction of shock waves and natural materials has been learnt – especially in the last decades – from dedicated numerical modelling. However, I perceive a serious shift from hands-on field work and mineralogical-geochemical lab studies to the modelling sphere. There is still a lot to be learnt and resolved from the last geological and laboratory investigations, and new generations of geologists should not be deterred to tackle the many open problems in these fields.

RECOGNITION OF TERRESTRIAL IMPACT STRUCTURES, PART 2: METEORITIC COMPONENTS, SHOCK EFFECTS, AND OTHER CHARACTERISTICS.

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Introduction: Impact craters on Earth are difficult to recognize because of the active geological processes that constantly reshape the Earth's surface. Depending on the age of the crust, the intensity of local geological processes, and other factors, such as accessibility or vegetation cover, known impact craters show a rather irregular distribution on the Earth's surface; in contrast to their formation, which is evenly distributed. There are a set of commonly accepted impact characteristics, including the finding of meteoritic components in impactites and/or the discovery of the effects of high (shock) pressure in crater rocks.

Identification of Terrestrial Impact Structures: All bodies in the solar system that have solid surfaces are covered by craters. In contrast to many other planets and moons in the solar system, the recognition of impact craters on the Earth is difficult, because active geological and atmospheric processes on our planet tend to obscure or erase the impact record in geologically short time periods. Impact craters must be verified from the study of their rocks — remote sensing and geophysical investigations can only provide initial hints at the possible presence of an impact crater or supporting information. Craters of any type and morphology are not a common landform on Earth. About 190 impact structures are currently known on Earth. Considering that some impact events demonstrably affected the geological and biological evolution on Earth, and that even small impact events (or atmospheric explosions known as airbursts) can disrupt the biosphere and lead to local and regional devastation, the understanding of impact structures and the processes by which they form is of broad interest.

Impact craters (before post-impact modification by erosion and other processes) occur on Earth in two distinctly different morphological forms. They are known as simple craters with diameters up to about 2 to 4 km, and complex craters, which have larger diameters. Complex craters are characterized by a central uplift in the form of either a central peak or a central ring of hills. As noted above, the recognition of geological structures and ejecta layers on Earth as being of impact origin is not easy. Even though morphological and geophysical surveys are important for the recognition of anomalous surface or subsurface structural features, which may be deeply eroded craters or impact structures entirely covered by post-impact sediments, definitive confirmation of an impact origin requires the presence of specific evidence (see, e.g., [1-3] for details). Such definitive evidence was obtained in the case of the Santa Fe impact structure (even though the feature is so deeply eroded that its original extent has not yet been reconstructed).

This involves the need to obtain the information required for understanding the ultra-high strain rate, high-pressure, and high-temperature impact process. This involves either shock metamorphic effects in minerals and rocks, and/or the presence of a meteoritic component in these rocks. In nature, shock metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. A wide variety of microscopic shock metamorphic effects have been identified. The most common ones include planar microdeformation features; optical mosaicism; changes in reflective index, birefringence, and optical axis angle; isotropization (e.g., formation of diaplectic glasses); and phase changes (high-pressure phases; melting). For the determination of the impact origin of a geological feature, the proper identification of either shock metamorphic evidence or the presence of extraterrestrial component is necessary. The presence of “spherules” of any sort, often cited in favor of an impact origin, is by itself NOT unambiguous or unique evidence for impact.

Although projectile fragments rarely survive an impact event, detectable amounts of melted and recondensed projectile are often incorporated into impact-produced breccias and melt rocks during crater formation. This dispersed projectile (meteoritic) material can be conclusively identified by distinct chemical and isotopic signatures in the host rocks, thus providing reliable evidence for a meteorite impact event. Geochemical lines of evidence can include the following: elevated platinum-group element (PGE) abundances and interelement ratios (with the caveat that in some cases terrestrial geological processes can lead to increased abundances) and (better) various isotopic compositions, such as characteristic Os, Cr, or W isotopic ratios. Similar to other aspects of impact studies, geochemistry is vulnerable to overinterpretation and wishful thinking. It is imperative that data be carefully obtained and verified, using independent methods and multiple laboratories, and that they be calibrated with the appropriate methods and standard reference materials. In summary, it is important that lines of evidence are seen in context and not in isolation. Any “new and unique” methods or observations have to first be verified at confirmed impact sites.

SHOCK DEFORMATION AT DEGRADED IMPACT CRATERS: THE SANTA FE STRUCTURE
A. J. Cavosie
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Introduction: Documenting diagnostic evidence to confirm hypervolcity deformation at ancient or degraded impact structures remains a challenge for recreating the terrestrial impact history. This challenge is magnified for investigations focusing on the the early Earth, but equally applies to any poorly preserved structure. Santa Fe is a confirmed impact structure located near the city of Santa Fe. Its age is likely Mesoproterozoic to Paleozoic [1-3]. Its size is also poorly known, but may be ~9-12 km in diameter based on scaling laws. The focus of this review is to summarize evidence of shock deformation reported at the Santa Fe impact structure in the broader context of considering how best to document diagnostic impact evidence at degraded impact structures.

Evidence of Impact at Santa Fe: The principle challenges in studying the Santa Fe impact structure is that it is tectonically dismembered, it may be bound by fault blocks, it is deeply eroded, and it is located in a high-relief, forested area with a complex geologic history spanning nearly two billion years. No geomorphic structural features (e.g., rim or central uplift) or geophysical anomalies suggestive of an impact structure have been reported. While regional occurrences of brecciated granite have been reported, no unequivocal impact melt rocks or breccia definitively related to impact have been described. Despite these challenges, evidence for diagnostic shock deformation have been documented in both bedrock and sediment with sufficient detail to confirm an impact origin.

Shatter Cones and Shocked Minerals: Shatter cones at Santa Fe occur in granitoid, schist, and amphibolite, and are well-exposed along Highway 475 [1-3]. Shocked quartz grains with decorated planar deformation features (PDF) in (0001) and {11-21} were documented in some shatter cones [1]. Detrital shocked quartz with decorated PDFs (Fig. 1A) has also been found in local drainages [4]. Shatter cones and shocked quartz have been interpreted to record conditions <10 GPa [1]. Xenotime with deformation twin lamellae in {112} (Fig. 1B) were documented in a shocked-quartz-bearing shatter cone in granite [5]. While formation of twin lamellae in xenotime has not been calibrated by experiment, the presence of shocked quartz with decorated PDFs and the absence of high-pressure YPO₄ phases were cited to interpret formation conditions from 5 to 20 GPa [5]. Zircon grains with {112} shock twin lamellae (Fig. 1C) have recently been described from Santa Fe; they occur as detrital grains, and also in shatter cones [2,3]. Shock-twins in zircon form at 20 GPa or higher [6], and thus represent the highest pressure phase thus far reported from the Santa Fe impact structure. Other putative shocked minerals have been reported from Santa Fe, including shocked apatite [7] and shocked muscovite [8], however the conditions under with impact-generated microstructures form in these minerals have not been well-calibrated.

Conclusion: Santa Fe is a case study that highlights challenges to discovery of new impact structures. One can ask, in the absence of shatter cones, would the Santa Fe structure have been discovered? And what if the majority of intact impact structures that are not buried have been described- what’s next? Our studies at Santa Fe and elsewhere highlight the application of new shocked accessory minerals such as xenotime [5,9], and also the ubiquitous presence of detrital shocked minerals that preserve evidence of eroded impact structures in the sedimentary record [10].

DETTRITAL SHOCKED ZIRCON PROVIDES NEW CONSTRAINTS ON THE AGE AND SIZE OF THE SANTA FE IMPACT STRUCTURE, NM (USA)
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Introduction: Terrestrial impact structures are prone to erosion, burial and tectonic deformation, providing incentive to further develop new methods for the reconstruction of the impact record on Earth. Shocked zircon has been previously reported to survive both extreme distal fluvial transport in modern alluvium and colluvium at distances up to ~2000 km [1] from the Vredefort Dome (South Africa), and in Holocene glacial deposits at Sudbury (Canada) [2]. Zircon {112} twins are considered diagnostic evidence of shock deformation, and have been identified at several impact structures such as Vredefort [1,3,4,5], Sudbury [2], Ries [6], Rock Elm [7], and in lunar impact breccia [8]. Shocked minerals, such as xenotime, apatite, and quartz, have previously been reported at the Santa Fe impact structure [9,10]. Here, we report the first occurrence of shock-twinned zircon from both sediments and bedrock, sampled away from known shatter cone localities at the Santa Fe impact structure [11].

Background: The Santa Fe impact structure is one of only five confirmed impact structures in western USA [12], and is located ~8 km northeast of Santa Fe, New Mexico. Shocked rocks are best exposed in Proterozoic crystalline basement rocks that outcrop along Highway 475 and contain well-formed shatter cones [11]. The basement uplift where shock-deformed rocks are located is called the Santa Fe Range, which is comprised of Proterozoic intrusive igneous and supracrustal rocks. The occurrence of shatter cones and planar deformation features in quartz confirmed this impact structure [11]. The impact age and crater diameter have been estimated to range from 350 – 1200 Ma and 6 – 13 km, respectively [11]; however, both are poorly constrained.

Samples and Methods: Detrital zircon grains from thirteen colluvium and two alluvium samples were hand-picked and placed onto scanning electron microscope (SEM) stubs from thirteen colluvium and two alluvium samples. Two shatter cones were also analyzed to search for shocked zircon in bedrock. Backscattered electron images were obtained using a Hitachi S3400 SEM at the University of Wisconsin-Madison. Electron backscatter diffraction (EBSD) maps were obtained using a Tescan Mira3 field emission gun SEM in the John de Laeter Center (JdLC) at Curtin University. Detrital zircon U-Pb ages were obtained using the sensitive high resolution ion microprobe (SHRIMP II) at the JdLC. Additional U-Pb analyses on grains from five samples, which include three samples that contain shocked grains and two others collected in proximity to those locations, were made via laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) in the JdLC.

Results: A total of 6619 grains from the fifteen sediment samples and two rock samples were surveyed; seven shocked grains were identified (7/6619 = 0.1%). One shocked grain was identified in a shatter cone of biotite schist. Of the seven shocked zircon grains, five were EBSD mapped, and three were analyzed with multiple SIMS spots. EBSD mapping revealed {112} deformation twin lamellae in each of the five zircon grains. U-Pb geochronology for three grains yield crystallization ages from 1715±22 to 1472±35 Ma. LA-ICPMS U-Pb ages provide information on the crustal age structure of the bedrock surrounding the impact structure.

Conclusion: This study revealed the first confirmed shocked zircon at Santa Fe by surveying ~6600 detrital zircon grains. Zircon, in addition to xenotime and quartz, is the third confirmed shocked mineral occurring at Santa Fe; its occurrence indicates that exposed bedrock experienced shock pressures of at least 20 GPa. The crystallization age for a shocked zircon of 1472±35 Ma offers the first reliable maximum impact age constraint. The new detrital shocked zircon sites indicate that shocked rocks and minerals are distributed over an area of 9 km² from which scaling laws indicate a crater diameter of 9 – 14 km.

Geologic History of the Santa Fe region

The oldest rocks of the southernmost Sangre de Cristo Mountains are ~1.72 Ga metavolcanic and ~1.65 Ga metasedimentary rocks that accreted to Laurentia in the Paleoproterozoic (Karlstrom et al., 2004). These rocks were intruded and locally contact metamorphosed by ~1.60-1.65 Ga granites (Karlstrom et al., 2004) (Table 1). The Proterozoic makes up ~5% of New Mexico, and is found as basement in drill holes throughout the state (Karlstrom et al., 2004). During both the Mississippian (~340 Ma) and Pennsylvanian (~310-315 Ma) Periods, sedimentary rocks were unconformably deposited in a shallow sea on the Proterozoic rocks. Paleozoic rocks have largely been eroded, but some Mississippian and the Pennsylvanian Madera Limestone overlie the Proterozoic rocks. Towards the end of the Pennsylvanian, the Ancestral Rocky mountain orogeny influenced the southeastern extent of the southern Sangre de Cristo Mountains. The contractional Laramide orogeny, occurring ~80-35 Ma caused the southern Sangre de Cristo Mountains to be exhumed again. Figure A on the right (Montalvo et al., in review) displays a timeline for geologic events in northern New Mexico.

### Table 1

<table>
<thead>
<tr>
<th>Event</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7 Ga metagranitic and metasedimentary rocks intruded by ~1.4 Ga granites</td>
<td>1.7 – 1.4 Ga</td>
</tr>
<tr>
<td>Faulting (Sanders et al., 2006)</td>
<td>1 Ga</td>
</tr>
<tr>
<td>More faulting (Sanders et al., 2006)</td>
<td>750 Ma</td>
</tr>
<tr>
<td>Mississippian and Pennsylvanian sedimentation (i.e., Madera Limestone deposited on shatter cones and breccias)</td>
<td>340 – 270 Ma</td>
</tr>
<tr>
<td>Pennsylvanian - Permian Ancestral Rocky Mountain surface uplift</td>
<td>300 – 230 Ma</td>
</tr>
<tr>
<td>Mesozoic burial?</td>
<td>?</td>
</tr>
<tr>
<td>Laramide Orogeny</td>
<td>80 – 35 Ma</td>
</tr>
<tr>
<td>Erosion of Laramide surface uplift</td>
<td>45 Ma – present</td>
</tr>
<tr>
<td>Magmatic episodes throughout late Eocene to early Miocene</td>
<td>33 – 20 Ma</td>
</tr>
<tr>
<td>Surface uplift of Rocky Mountains, subsidence of Rio Grande Rift</td>
<td>26 Ma – present</td>
</tr>
<tr>
<td>Infilling of Rio Grande Rift with Santa Fe Group sediments</td>
<td>25 Ma – present</td>
</tr>
</tbody>
</table>
Sunday’s field trip will focus on shatter cones discovered in 2005 (McElvain et al., 2006), fault breccias from the Borrego Fault zone (Read et al. 2000), and peculiar breccias found as clasts in the fault breccia. The Picuris-Pecos Fault ~18 km to the east of the field trip area will be discussed due to the similarity of its breccia to “breccia towers” seen today, but not visited (Bauer and Rasler, 1995; Wawrzyniec et al., 2007; Cather et al., 2011; Luther et al., 2012). See geologic maps of New Mexico for locations (Wilks, 2005).

The earliest geologic maps of Santa Fe noted much brecciation that did not conform to structural measurements and the local tectonic and geologic history (Spiegel and Baldwin, 1963; Kottlowoski et al., 1963). Granodiorite was described as “highly fractured and brecciated” and leucogranite as “a minor unit that consists of several rock types … poorly exposed and commonly fractured and brecciated” (Bauer et al., 1996). Since the discovery of shatter cones in 2005, the area has been of more interest to researchers. A high measurement of iridium was reported (Caine, 2007; Caine et al., 2017), but not high enough (~20 ppb) to be considered an anomaly. This field guide summarizes the earliest geologic mapping efforts by University of New Mexico researchers as the first field trip (pages 3 to 10) and investigations regarding detrital shocked mineral grained as the second field trip (pages 11 to 20).

**Preparation and cautions for both field trips:**

**Items to bring:** Sun protection (hat, sunscreen), water (~1 liter)

**Physical activity:** Walking on trails and hillslopes; some walking areas will be sandy or rocky; sturdy walking shoes are required. One site is ~100m from the parking spot. In general, there are no strenuous or challenging activities that are required to visit these sites.

**Possible hazards:** falling/stumbling on loose gravel or rocks; dehydration; sunburn; crossing roads; some wildlife.
Shatter cones and breccias of the Santa Fe impact structure

Field Trip days/times: Sunday, July 23rd 1:30 to 4:30; Wednesday, July 26th 3:00 to 6:00 PM

Field trip leaders: Shawn Wright, Aaron Cavosie, Horton Newsom, Pedro Montalvo

Road Log

Set odometer to 0.0 to start Road Log on a right turn as Washington St. becomes Artist St.

0.0 Santa Fe: Intersection of NM 590 (Washington St.) and NM 475 (Artist St. becomes Hyde Road). Follow NM 475.

1.7 Just past the gate for the Santa Fe Institute, on the left, shattered granitic gneiss cut by fractured post-metamorphic pegmatite dikes.

2.2 Biotite schist blocks in brecciated granite gneiss.

2.6 Drivers: Note large parking lot to left of Sierra del Norte road. This will be the final stop of the day.

3.2 – 3.3 On roadcuts to left, note metagranite intruding into schist.

4.1 Nun’s Curve (Figure 1) is named for a tragic accident. Please use caution. On the right (south), excellent exposures of breccias, with meter-sized blocks of Proterozoic schist and gneiss as clasts, overlain by Paleozoic carbonates. The contact appears to be depositional, and hence Proterozoic breccia was the paleosurface before the sea level rose. In the distance to the left, the same contact can be seen on a high ridge, cut by faults.

Figure 1. Nun’s curve at 4.1 miles showing the contact of brecciated basement with the overlying Mississippian sediments.
4.4 Trailhead (to right/north) and parking (to left/south) for Little Tesuque Creek Trailhead. This will be Stop 2 later today.

4.8 To north/left, note memorial(s) (due to a bus accident) on side of the road below Breccia Tower #1. We named the breccia towers from east to west, and this is the most eastern. We will not stop here because we will visit Breccia Towers #2 and #3 at Stop 2.

5.3 Another “tower” is visible on hillside to left after a left turn, but this one is a pegmatite vein and not breccia. Highest peak seen in front of vehicle has shatter cones near top (Fackelman et al., 2008), but most are talus.

5.5 Chamisa Trailhead is on the left. We will stop to the right later on Sunday for field trip participants to search for shatter cone talus, and on Wednesday’s field trip that focuses on shocked detrital minerals.

5.9 Continue on Highway 475 and pull over to right at 5.9 miles where concrete barriers are seen to left (Figure 2). It is suggested that drivers pull in-and-around such that the vans/buses face the road (for ease when leaving and to prevent “backing out”).

Stop 1. Shatter cone outcrop

SAFETY WARNING: The road is curvy and downhill, and thus limited visibility and a short reaction time for drivers. Use extreme caution when crossing the street – there is not a crosswalk. Our suggestion is to look both ways, listen for vehicle sounds, and then RUN/JOG to the concrete barriers. Sit on the top and swing your feet over quickly. DON’T walk to the barriers and then walk in the road around them – this approach results in you being in the road too long.

Figure 2. Shatter cone outcrop.
These outcrops went unnoticed until local petroleum geologist Tim McElvain found them in 2005 (McElvain et al., 2006). Dr. McElvain remains a supporter of Santa Fe research and received an honorary doctorate from UNM in 2009.
Likely, these shatter cones represent a central peak of a complex crater (Fackelman et al., 2008). Petrography of the shatter cone surfaces reveals planar deformation features in quartz (Fackelman et al, 2008) that are indicative of shock metamorphism.

Drive back west towards the city of Santa Fe. At mileage 7.4, we want to park on the left, but must turn the vehicles around to conform to county law. U-turn and park on the right or south side. There may be several vehicles on the weekend. Cross the street on foot quickly and carefully. The trailhead is on the north side of the road to the west.

**Stop 2. Little Tesuque Creek Trail to breccia outcrops**

Note roadcut on north side of road (Figure 3 to right). Proterozoic gneiss, granite, and biotite schist, with local intrusions and pegmatites, are found throughout New Mexico, but the pervasively fractured texture is unique. Shatter cones and breccias are not found anywhere else in the Proterozoic in New Mexico (Karlstrom et al., 2004).

Cross to the northern side of Highway 475 and walk ~50 meters west down the trail to Breccia Tower #2.

This tower (Figure 4) is one of several that align to the NNW from the shatter cone exposures. We will visit the second and possibly the third towers. Granite gneiss clasts are centimeters to ~1 meter in size. The matrix consists of shards of granite gneiss. No Paleozoic limestone is evident. There is some evidence for horizontal zoning, which suggests emplacement via vertical movement. The interpretation is that the present breccia is likely a fault breccia.
Figure 4. Base of Breccia Tower #2. The height of Breccia Tower #2 (~25 meters) indicates at least that much erosion. The vertical extent below the surface is not known but deserves future study.

Figure 5. Schematic diagram of central peak formation (French, 1998) with modifications showing post-impact modification (Osinski et al., 2005) and present-day erosion level illustrating the potential current state of the Santa Fe impact structure after several kilometers of erosion. The breccia towers, while perhaps not original impact breccias, could possibly be related to faults resulting from the impact event.
Figure 6. Topography and early mapping efforts (Tegtmeier et al., 2008) show the relationship of the shatter cones (blue triangles) to Breccia Towers (orange circles). The green box is the area shown in Figure 8 of Hyde Memorial State Park.

Scanning Electron Microscopy of Breccia Towers

Figure 7. SEM images of Breccia Towers show metagranite clasts (solid greys and whites are quartz and alkali feldspar) in a fine-grained matrix (comminution running from left to right in the 1st image and from top to bottom in the 2nd image). This is different from SEM images of Breccia Type 2 shown in Figure 11. Scale bar in upper left corners both measure 500 µm.
Explore on your next visit: Hyde Memorial State Park

Hyde Memorial State Park is a dumbbell-shaped region measuring 350 acres along Highway 475. The Borrego Fault runs through the middle of the park (Figure 8). The east side has been faulted to the south and/or the west side to the north. Thus, because the shatter cone occurrences terminate at the Borrego Fault on the west side, it is possible that shatter cones exist to south (Figure 6). These woodlands to south are remote with no real road access, so detailed investigations wait.

Figure 8. General geologic map of Hyde Memorial State Park from NMBGMR.

Drive south, then west, on Hyde Park Road back towards Santa Fe and turn right on Sierra del Norte Street. Pull into Dale Ball Trail parking lot (Figure 9), and assemble at trailhead at bottom of hill.
Stop 3. Breccias at Dale Ball North Trail

Odd breccias (Wright et al., 2010) are found as talus and rare outcrops to the north of the parking lot.

As you walk around the trails (and off trails), be on the lookout for breccias (Figure 10 below).

Petrography and SEM of these breccias reveal interesting characteristics that are different from the breccia towers (Figure 6). The matrix appears to be the same lithology as the clasts with no comminution and little to no alteration except for hematization (Figure 11).

Figure 9 (right). Topographic map of Dale Ball North Trail.

Figure 10. Hand samples of breccias from the Dale Ball North Trail in the field (above) and a cut slice to right.
Figure 11. Comparison of SEM images of Breccia Types #1 and #2. In both images, a clast in the breccia is shown at the top of the BSE image, and the matrix is shown as the bottom (or lower right ¼ of the BSE image of Breccia Type #2 on the right). Unlike the Breccia Towers (Breccia Type #1), the matrix of Breccia Type #2 (BT2) is not easily discernable. The matrix and clasts are nearly identical – metagranitic quartz and alkali feldspar, though cross cutting relationships can be seen if you look closely at the shades of grey. Our preliminary interpretation is that the matrix of BT2 was melted and recrystallized. In at least one Breccia Tower, clasts of Breccia Type #2 can be found within Breccia Type #1. Superposition suggests that Breccia Type #2 is from an earlier brecciation event – either an earlier fault or perhaps impact.
Assembling Evidence of Impact at Highly Deformed Impact Craters:
Detrital Shocked Minerals Grains

Fieldtrip Guide to Stops of Interest

Wednesday July 26, 2017

Field trip leaders: Aaron Cavosie; Pedro Montalvo; Shawn Wright

Duration: the trip will run at 1:30 PM (departing at 1:15 PM)
(note: a different trip will run at 3:30 PM, departing at 3:00 PM)

Items to bring: Sun protection (hat, sunscreen), water (1-2L), snack (if desired).

Physical activity: Walking on trails and hillslopes; some walking areas will be sandy or rocky (valley bottoms, drainages, etc.), so sturdy walking shoes are required. One site is ~100m from the parking area. The other involves walking ~0.5-0.6 km and back. There will be opportunities to climb on and examine craggy outcrops, but this is not required. In general, there are no strenuous or challenging activities that are required to visit these sites.

Possible hazards: falling/stumbling on loose gravel or rocks; dehydration; sunburn; crossing roads; animals (bears, rattlesnakes, and scorpions are present in the Santa Fe range, but are unlikely to be encountered in the areas we will visit).

Objectives. The goal of the Wednesday field trip is to introduce the use of detrital shocked mineral surveys as a means for detecting the presence of shocked bedrock at structures that are difficult to study due to poor exposure, uncertain field relations, or other aspects. We will examine bedrock at new sites where detrital shocked minerals have been discovered.

Location. We will start from the main parking area at Chamisa trailhead on NM state highway 475 (an area visited during the Sunday field trip). This is one of the main parking areas on Hwy 475 for those wanting to access local hiking trails (Fig. 12).

Stop 1 is a locality on the north side of Hwy 475. From Chamisa trailhead, we will walk to the hillslope immediately on the west side of the broad open valley. Stop 2 is a locality south of Hwy 475. From Chamisa trailhead, we will walk along a dry drainage in a southeast direction.

Figure 12. Satellite image (Google Earth) showing intersection of Hwy 475 (east-west) with Chamisa trailhead (going north). The locations of Stop 1 and Stop 2 are indicated. Both are <0.5 from the car park area.
Introduction to detrital shocked minerals.

Shocked minerals are one of the most commonly sought lines of evidence used to confirm an impact origin for a suspected crater, as they only form as a result of hypervelocity processes. Microstructures attributed to shock deformation have been reported in many minerals, but it is probably the case that quartz is most often the mineral used to confirm the presence of shock deformation (Stöffler and Langenhorst, 1994). However, a suite of accessory minerals found in a wide range of bedrocks are increasingly being recognized as preserving reliable evidence of shock deformation. Of these, zircon is probably the most widely applied (e.g., Krogh et al., 1984 and many others since). Other shocked accessory minerals, including monazite (Erickson et al., 2016), xenotime (Cavosie et al., 2016), baddeleyite (Darling et al., 2016), and apatite (Cavosie and Lugo, 2014) are increasingly being used to quantify evidence of hypervelocity deformation, and also in some cases, impact conditions.

All of the above shocked minerals, including quartz, survive as detrital grains when craters erode, and thus preserve evidence of impact in the sedimentary record (Fig. 13). Detrital shocked minerals have been described from the Vredefort (quartz, zircon, monazite, xenotime; Cavosie et al., 2010; Erickson et al., 2013a,b; Montalvo et al., 2017; Cavosie et al., 2017- Metsoc abstract), Sudbury (quartz, zircon; Thomson et al., 2014), and Rock Elm (quartz; Roig et al., 2013) impact structures. It is instructive to distinguish detrital shocked minerals, which originate in any lithology, and have been transported some distance by sedimentary processes; from shocked detrital minerals, which can be found at any crater that exposes sedimentary rocks, and do not require post-impact transport. We will visit stops where detrital shocked minerals have been discovered at the Santa Fe impact structure.

Figure 13. Examples of detrital shocked minerals. A. Shock-twinned zircon (left) and quartz with decorated PDFs from the Sudbury basin in Canada (Thomson et al., 2014). B. Shocked zircon (left) and quartz (right) with decorated PDFs from the Vredefort Dome impact structure in South Africa (Cavosie et al., 2010; Erickson et al., 2013a). C. Shocked quartz with planar fractures from the Rock Elm impact structure, USA (Roig et al., 2013).
**STOP 1. Chamisa trailhead.**
The north-trending Chamisa trail roughly corresponds to the western extent of the shatter cones described by Fackelman et al. (2008). Most shatter cone localities at the Santa Fe structure occur east of Chamisa trail, but Fackelman et al. indicated a few were found on the west side of the trailhead near Hwy 475. This raises the question as to the significance, if any, of Chamisa trail as a boundary. In other words, are shocked rocks definitively present west of Chamisa trail? If so, what is the western extent of the impact structure? The geological map of Bauer et al. (1996) indicates the presence of biotite granite (Xg) on both sides of the trail (Fig. 13). However, interleaved supracrustal rocks, such as amphibolite (Xa), schist, and quartzite (Xqf) are only present east of Chamisa trail; an inferred fault is indicated (Fig. 14).

![Figure 14. Geologic map showing area near Chamisa trailhead (Bauer et al., 1996). One of the outstanding questions we will use results from detrital shocked mineral surveys to discuss is if there is definitive evidence for the presence of shocked bedrock west of Chamisa trail.](image)
At **Stop 1** we will proceed from the parking area and walk to the low hillslope on the west side of the trail. At this location, little bedrock is exposed; the hillslope is mostly clay, as the granitoid bedrock is deeply weathered to a red-brown color (**Fig. 15**).

![Figure 15. View looking north along the weathered hillslope, west side of Chamisa trail (photo: A. Cavosie).](image)

There are several features to note at **Stop 1**. The first is that a series of gullies have eroded the hillslope, providing 3D access into the weathered material, some of which contain bedrock. The second is that multiple lithologies may be present, based on variations in the color of weathered rocks. The color variations are prominent in the field, and can also be seen on satellite images (**Fig. 16**). What do the color variations signify?

![Figure 16. Satellite image (Google Earth) showing a view of the hillslope to be visited at Stop 1. Note the differences in color.](image)
A recent study of detrital zircon grains from a modern colluvium sample collected from one of the gullies at Stop 1 by Montalvo et al. (in review; see also Montalvo et al., 2017 Metsoc abstract) reported the presence of multiple shocked zircon grains. The detrital grains preserve planar fractures that are visible on exterior surfaces using backscattered electron (BSE) imaging with a scanning electron microscope (SEM) (Fig. 17). The planar fractures occur as closely spaced sets, and occur in multiple orientations.

Figure 17. Planar fractures visible on the surface of a detrital zircon from the west side of Chamisa trailhead (Montalvo et al., in review).

The detrital zircon grains were subsequently polished, and analysed using electron backscatter diffraction (EBSD), an SEM-based method that can determine crystallographic orientation of polished samples by producing diffraction patterns as the electron beam steps across the sample. The spatial resolution of EBSD using a field emission SEM is routinely down to 50 nm. EBSD is thus ideal for detecting evidence of shock-induced deformation. In the case of zircon, there are two microstructures that are diagnostic of shock deformation: twin lamellae in \{112\}, and the high pressure ZrSiO₄ polymorph reidite.

Santa Fe zircon grains with deformation twins in \{112\} orientation were discovered during EBSD analysis. One grain contains planar fractures visible on the exterior surface (Fig. 18A), that correlate with twin lamellae in \{112\} orientation (Fig. 18B). The twin lamellae are misoriented (disoriented) by 65° about \{110\}, which can be observed readily as a pole figure plotted on a stereonet. The \{110\} pole figure shows a lower cluster of poles (mostly green), which is shared by both the twin and the host grain (Fig. 18C). It is about this axis that the upper cluster of \{110\} poles for the twin is rotated 65°, as indicated by the arrow. A consequence of this geometry is a shared \{112\} direction for the host and twin, also indicated by an arrow in the \{112\} pole figure.

Shock features in zircon. Several methods are available for documenting shock deformation in zircon, including Raman, transmission electron microscopy, and XRD. However, EBSD has revolutionized the study of shock microstructures and high pressure phases in zircon. A number of studies have used EBSD to document the presence of \{112\} deformation twins in zircon from impact environments (e.g. Moser et al., 2011; Timms et al., 2012; Erickson et al. 2013a,b; Thomson et al., 2014; Cavosie et al., 2015a,b; Erickson et al., 2016; Montalvo, S.D. et al., 2017). EBSD has also been used to document the presence of reidite (Cavosie et al., 2015a; Reddy et al., 2015; Erickson et al., 2017). The conditions under which \{112\} deformation twins form in shocked zircon are not known precisely, but are generally accepted to be >20 GPa based on available data from shock (Leroux et al., 1999) and static (Morozova, 2015) high-pressure experiments.
Figure 18. Shock-twinned detrital zircon from Stop 1. A. Backscatter electron images of the exterior surface showing planar fractures in two orientations. B. Orientation maps generated from EBSD data. A texture component (TC) map showing lattice misorientation up to ~10° relative to the location of the red cross in the lower left. An inverse pole figure map (IPF) shows crystallographic orientation relative to Miller indices; the polished surface is nearly parallel to {100}. The twin lamellae are misoriented from the host grain by 65°/<110>. C. Pole figures (lower hemisphere, equal area) showing poles to the main crystallographic axes. The data show in C correspond to the colors shown in the IPF map.
Significance of detrital shocked zircon at Stop 1.

Shocked zircon provides evidence that some exposed rocks at the Santa Fe structure experienced >20 GPa conditions. The presence of detrital shocked zircon in colluvium at Stop 1 begs several questions- What rock did they originate from? Are shocked rocks present on the west side of Chamisa trail? If so, to what extent? And how does this influence estimates for the size of the Santa Fe impact structure…?

A brecciated granite is present at Stop 1, proximal to where detrital shocked zircon was discovered. The breccia is distinctive at the hand-sample (Fig. 19, left) and in transmitted light (Fig. 19, right), and appears to be associated with the light-colored weathered material in outcrop. During our visit to Stop 1 we will explore gullies and local valleys to investigate the extent and character of the breccia. If it can be substantiated that the detrital shocked zircon grains in colluvium originated in breccia, it would provide the first unambiguous evidence that connects formation of breccia in the area to the Santa Fe impact event.

![Figure 19](image1.png)

**Figure 19.** Images of breccia collected from Stop 1. Left. Lightly polished rock slab, showing red granite clasts in a grey matrix. Right. Transmitted light image showing angular clasts of granite.

We will depart from Stop 1 by returning to the parking area where we will regroup, and then proceed southeast in a dry drainage towards Stop 2 (Fig. 20).

![Figure 20](image2.png)

**Figure 20.** Satellite view (Google Earth) looking west along Hwy 475. Both field trip stops are indicated.
STOP 2. Southeast of Chamisa trailhead, and south of Highway 475

The description of shatter cones at the Santa Fe impact structure by Fackelman et al. (2008) described their occurrence as being exclusively north of Hwy 475. This allows for the possibility that some type of tectonic structure (fault, etc.) occurs along the road that may represent the southern boundary of the impact structure. However, geologic mapping shows many units that are continuous, or nearly so, on both sides of Hwy 475, suggesting minimal offset along any east-west trending faults in this area.

In this context, Montalvo et al. (in review; see also Montalvo et al., 2017 Metsoc abstract) extended the search for detrital shocked minerals to locations south of Hwy 475, in order to search for evidence of as-of-yet undiscovered shocked bedrock. The result is that detrital shocked zircon grains were found in two separate valleys located south of Hwy 475; one of the sites is the location we will visit for Stop 2 (Figs. 21, 22).

Figure 21. Photo of Stop 2, a colluvium sampling site where detrital shocked zircon was found, ~0.5 km south of Hwy 475.

Figure 22. Photo showing the poorly sorted nature of the colluvium sampled at Stop 2. At sites such as this, sieving samples in the field provides a means to increase the volume of material sampled that is likely to contain detrital zircon (rock fragments are avoided). After sampling, we washed the sieves in Little Tesuque creek to ensure they were thoroughly clean prior to their next use.
Figure 23. Detrital shocked zircon grain from colluvium sampled at Stop 2. A. One orientation of well-developed planar fractures is visible on the exterior surface. B. A single orientation of \{112\} twin lamellae on the polished surface correspond to the same orientation as the planar fractures. C. Pole figures show the characteristic 65°/<110> relation between the host and twin for \{112\} twin lamellae. The arrow in the \{112\} pole figure indicates the shared orientation.

The detrital shocked zircon grains found south of Hwy 475 have the same overall characteristics as the ones found at Stop 1. Planar fractures are visible on the grain exteriors in BSE images, and EBSD revealed the presence of \{112\} deformation twin lamellae on polished surfaces (Fig. 23). In general, the grains are well-formed, but contain many irregular fractures, and are often broken. There is minimal evidence of sedimentary abrasion on grain surfaces, as would be expected for detrital grains in colluvium that are proximal to source rocks.
The location of Stop 2 differs in a number of ways from Stop 1. At Stop 1, the detrital shocked zircon grains were sampled from a small gully carved in a hillslope, where the source of the detrital grains can be assumed to be within the gully. In contrast, the detrital shocked grains at Stop 2 were sampled from poorly sorted colluvium (Fig. 21,22) from the bottom of a dry valley that continues south for another ~1 km. In other words, the detrital shocked grains could have originated from essentially any of the bedrocks exposed as far south as the drainage divide. The geologic map of Bauer et al. (1997) indicates that biotite granite (Xg), amphibolite (Xa), and schist (Xqf) are all present in the drainage basin (Fig. 24).

Figure 24. Geologic map of Bauer et al. (1997) of area around Stop 2. The dashed red line indicates the boundary of the drainage basin. The dominant rock type is biotite granite, but all of the lithologies present could potentially be the shocked bedrock source rocks for the detrital shocked zircon grains.

At Stop 2 we will examine outcrops of bedrock that are exposed in the vicinity of where the detrital shocked zircon grains were found (Fig. 25) to investigate if evidence of shocked bedrock can be detected.

Figure 25. Three solemn trunks near Stop 2 know where the shocked rocks are, but they aren’t in a talking mood.
References


Wilks, M.E., compiler (2005), New Mexico Geologic Highway Map: New Mexico Geologic Society and New Mexico Bureau of Geology and Mineral Resources, 1:1,000,000 scale.
