Pretoria Saltpan crater: Impact origin confirmed

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ABSTRACT

The origin of the well-preserved, 1.13-km-diameter Pretoria Saltpan crater in South Africa has been debated throughout this century. The structure of this Pleistocene crater resembles that of other simple, bowl-shaped impact craters, but the presence of volcanic intrusive rocks along the crater rim has suggested a cryptovolcanic origin. In 1989 a drill core from the crater became available. The core was studied in detail to establish a paleoenvironmental record for the mid-latitudes of the Southern Hemisphere by analyzing the undisturbed crater sediments that had accumulated since formation of the crater, and to determine the origin of the crater. The discovery of shock-metamorphosed quartz and feldspar fragments, melt breccia and siderophile element–enriched glasses, and sulfide spherules in crater breccia deposits provides clear evidence for the impact origin of the Pretoria Saltpan crater.

Figure 1. Panoramic view of Pretoria Saltpan crater from its northern rim.

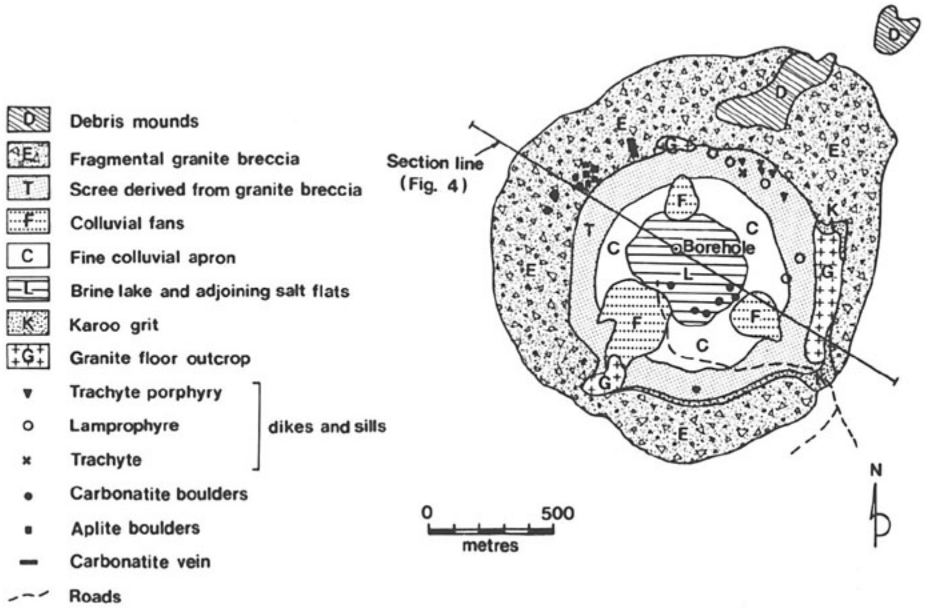

Figure 2. Geology of crater area (after Wagner, 1922; Feuchtwanger, 1973; our observations); section line is for cross section in Figure 4.

INTRODUCTION AND PREVIOUS STUDIES

The Pretoria Saltpan crater (Fig. 1) (lat 25°34′30″S, long 28°04′59″E, about 40 km north-northwest of Pretoria) has been on record as a unique feature of "volcanic origin" since the mid-1800s (Jeppe, 1868). Wagner (1922) concluded that the Saltpan crater was a "sunken caldera" of "cryptovolcanic" origin on the basis of a rim structure comparable to those from known calderas, the discovery of dolomitic breccia thought to be of volcanic origin, and his belief that the saline brines produced in the crater were volcanic emanations.

Rohleder (1933) was the first to suggest an impact origin for this structure. This was accepted by Leonard (1946), who included the Saltpan crater in his compilation of probable terrestrial impact sites. Milton and Naeser (1971) reported the discovery of small-scale but intense structural deformation in the crater rim, similar to that observed in confirmed impact structures such as Meteor crater in Arizona. A more detailed lithological map of the crater rim and floor by Feuchtwanger (1973) presented further evidence for volcanic activity in the area. In addition to the carbonate breccia described by Wagner (1922), trachyte, phonolite, and lamprophyre dikes (some thought to be ring dikes) were reported, in places associated with fenitization of the host rocks (Fig. 2).

The results of a gravity survey (Fudali et al., 1973) were interpreted as further support for Wagner's (1922) cryptovolcanic hypothesis. In none of these earlier studies were shock-metamorphic effects in any of the crater rock types reported. In the absence of such definitive evidence in favor of impact, the volcanic hypothesis remained widely accepted.

Nevertheless, both Milton and Naeser (1971) and Fudali et al. (1973) stated explicitly that conclusive evidence could be provided only by drilling into the crater. This core from the borehole became available in 1989. Since then, a multidisciplinary team has pursued detailed studies with two main objectives: (1) to obtain conclusive evidence for the origin of the structure, and (2) to provide a paleoenvironmental record for the middle latitudes of the Southern Hemisphere (Scott, 1988). Herein we document stratigraphic, petrographic, and chemical results from these studies and discuss the importance of the Pretoria Saltpan in comparison with other small, bowl-shaped impact structures.

GEOLOGY OF THE CRATER

The Saltpan crater (Fig. 1) is a nearly circular structure with a rim-to-rim diameter of 1130 m. Maximum rim elevation above the present crater floor is 119 m, but the rim is only 60 m above the surrounding plains. The crater (Fig. 2)

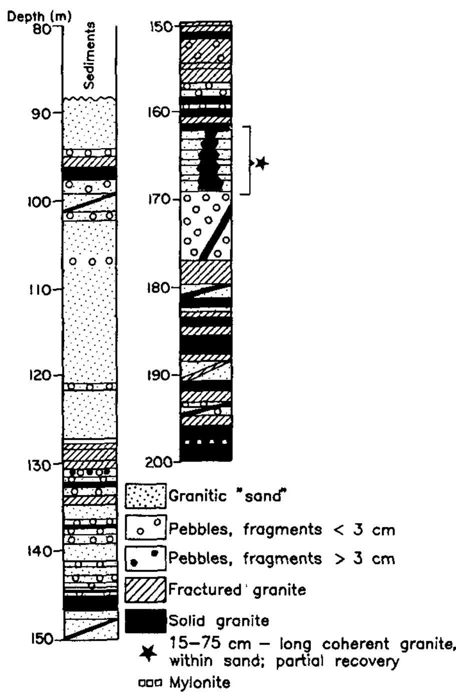

Figure 3. Schematic presentation of borehole stratigraphy. Above 90 m depth only lacustrine sediments were intersected.

was formed in 2.05 Ga Nebo granite of the Bushveld Complex (Walraven et al., 1990). Small amounts of mafic and alkaline intrusive rock are present in the rim granite. Some of these dike- or sill-like intrusives tend to be distributed radially or concentrically relative to the crater center. The crater rim is covered partly by Karoo grit, which is overlain by fragmental granitic breccia (Fig. 2). Several fragments of granitic cataclasite and granite with veins up to several millimetres wide of altered cataclasite (or pseudotachylite?) were found on the crater floor; such breccias are also exposed in the rim in contact with veins of altered carbonatite or trachyte. The crater floor lies below the ground-water table, resulting in a shallow central lake filled with a highly saline brine (Ashton and Schoeman, 1983).

Zircon and apatite fission-track ages for altered carbonatite are 1.9 ±0.4 and 0.6 ±0.09 Ga (Milton and Naeser, 1971), and K-Ar and Rb-Sr biotite ages for lamprophyre range from 1.3 to 1.4 Ga (Partridge et al., 1990; Reimold et al., 1991). These ages are incompatible with the excellent preservation state of the Saltpan. Furthermore, a late Pleistocene age of ca. 200 ka for the crater was estimated through extrapolation of accumulation rates based on ^{14}C dating of upper lacustrine sediments (Partridge et al., 1992).

Fudali et al (1973) concluded from their gravity data that the crater had the form of a simple but asymmetrical bowl, and that the crater fill consisted of a layer of crater sediment above loosely consolidated breccia. The stratigraphic record of the 1989 borehole (Fig. 3) agrees well with this gravity model: 90 m of lacustrine crater sediments with a few debris flows are underlain by a 53-m-thick unit of unconsolidated fragmental breccia consisting of granitic sand intercalated with fractured granite boulders (5 cm to 1.5 m in diameter). The sands contain <2 vol% of diatomite, siltstone, and shale of probable Karoo age (ca. 200 ±50 Ma). Below this breccia, strongly fractured and locally brecciated Bushveld granite is present. The amount of solid granite gradually increases to a depth of 200 m (Fig. 3), where drilling ended.

Between 108 and 120 m and at 139 m depth there are several strongly oxidized goethite-rich layers as wide as 25 cm. Sieving revealed abundant, up to 2-cm-diameter and commonly strongly altered melt breccia fragments (also termed agglutinates). They are composed of angular lithic and mineral clasts, derived from Bushveld granite, set in a slightly oxidized, yellowish glass. Such melt breccia fragments were subsequently observed in small numbers at all depths between 90 and 143 m. No volcanic rocks were intersected by this borehole, and modal analysis showed that the fragmental breccia contains <0.005 vol% of a potential volcanic component (pyroxene grains). Figure 4 is a schematic cross section through the crater that is based on the bore-hole stratigraphy.

A circular depression ~200 m in diameter, located about 1 km south of the Saltpan, suggests the possibility of a twin crater.

PETROGRAPHIC AND CHEMICAL RESULTS

Partridge et al. (1990) studied 65 specimens of fractured and brecciated drill-core or crater-rim granite for deformation effects. Not even those core or rim samples that showed a strong degree of brecciation revealed significant microdeformation. Single shear fractures, sometimes connected by sets of extension fractures, were observed near grain boundaries only in a few quartz grains. Cataclasite—float samples or from contact zones along trachyte—displayed no deformation other than undulatory extinction in quartz and rare kink banding in mica.

Grain mounts of 31 samples from the uncon-

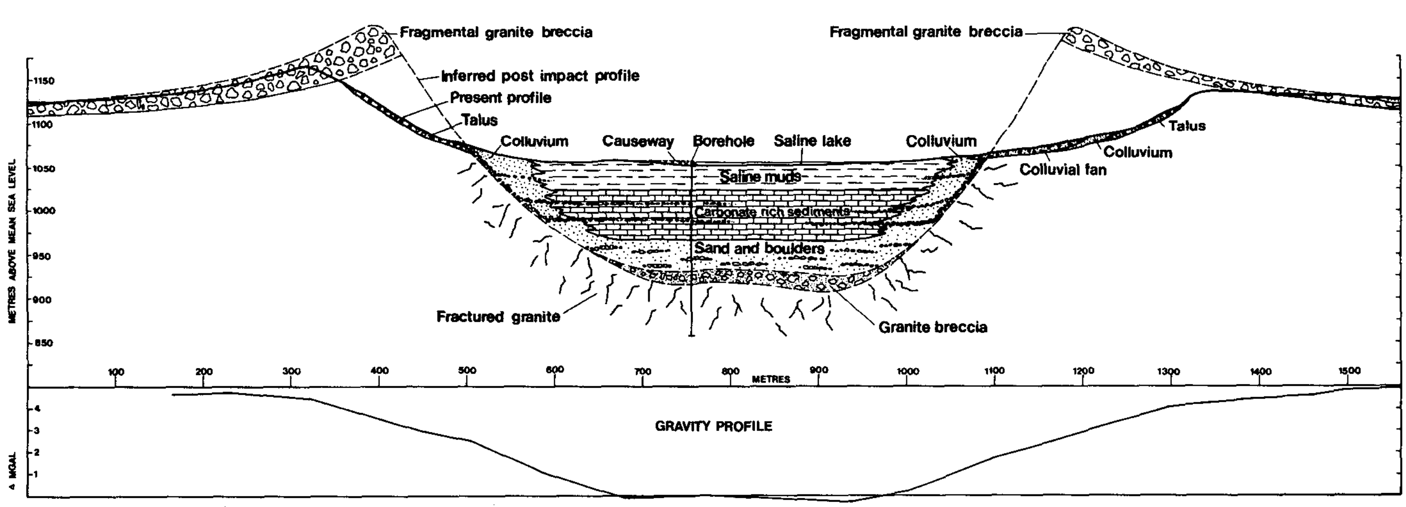

Figure 4. Cross section through Pretoria Saltpan impact structure, constructed with data from Fudali et al. (1973), Feuchtwanger (1973), and this study (bore-hole stratigraphy).

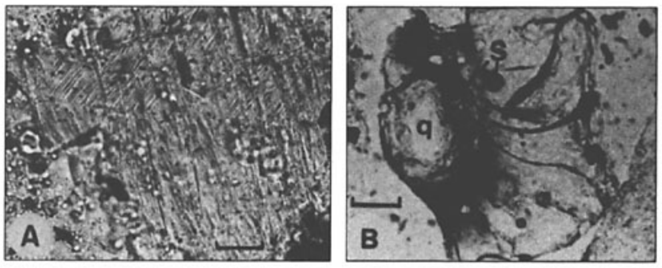

Figure 5. A: Quartz grain with two sets of planar deformation features from 103 m; parallel nicols; scale bar = 33 μm. B: Glass fragment, from 91.5 m, containing quartz (q) clast and two sulfide (S) spherules; parallel nicols; scale bar = 40 μm.

TABLE 1. MEAN COMPOSITIONS OF SALTPAN CRATER ROCKS

	Granite	1σ	Breccia	1σ	Glass	1σ	Agglu- tinate	1σ	Sulfide Spherules	1σ
SiO_2	74.4	3.1	73.7	0.7	73.2	5.5				
TiO_2	0.25	0.07	0.24	0.01	0.27	0.07				
Al_2O_3	11.2	1.1	11.4	0.15	11.9	3.0				
Fe_2O_3	3.3	0.8	3.6	0.58	5.6	1.3				
MnO	0.02	0.02	0.04	0.01	0.12	0.03				
MgO	0.07	0.1	0.15	0.09	2.3	0.8				
CaO	0.95	0.3	1.2	0.2	0.7	0.25				
Na_2O	2.7	0.55	3.1	0.1	2.3	0.3				
K_2O	4.95	0.5	4.8	0.06	3.4	0.6				
P_2O_5	0.03	0.01	0.04	0.01	0.02	0.02				
LoI	0.9	0.6	1.6	0.4	0	0				
Total	98.77		99.87		99.81					
Cr	2.23	1.0	36.2	2.4	285	7.8	224	114	218	18
Co	3.2	2.8	45.6	17.4	57.6	3.0	347	393	120	26
Ni	<20		40.0	5.0	1170	30	200	20	1000	500
Ir	<2		3.7	2.9	4.25	1.25	4.5	0.5	75	25
Au	5.45	1.5	3.8	4.2	3	1	2.1	0.6	183	3

Note: Major element oxides (weight percent) determined by X-ray fluorescence; trace elements (parts per million, except Au and Ir, which are parts per billion) determined by instrumental neutron activation analysis.

solidated breccia from depths between 90 and 143 m were prepared. All the samples exhibited clear evidence of shock metamorphism (examples in Fig. 5). During a scan of about 80000 particles, 357 (0.45 vol%) grains of shock-metamorphosed quartz, 64 particles of shocked plagioclase and K-feldspar, and 908 (1.14 vol%) glass fragments and spherules, larger than 100 μm, were counted. Melt breccia was observed to be most abundant below 139 m. Shock-metamorphosed quartz occurs with single or multiple sets of planar deformation features (PDF; Grieve et al., 1990) with up to six crystallographic orientations per grain, as diaplectic quartz glass, and as partially or completely isotropized grains. These deformation effects correspond to shock-metamorphic pressures from about 15 to 35 GPa. The same shock-metamorphic phenomena were observed in feldspar grains. Figure 6 demonstrates the variation in abundance of shocked particles with depth. With the exception of the distribution of melt breccias, all other features are most abundant between about 110 and 125 m depth.

Melt breccia particles are similar to the much larger ejecta breccias described from other impact structures. Glass spherules and shards are translucent, greenish or brownish, and some display schlieren of different colors. Their shapes are highly variable: perfect spherules, droplets, barbells, irregularly broken shards, and rods are abundant. Although smaller, they resemble impact glasses such as those described from the Ries (Graup, 1981) and Manson (Koeberl and Hartung, 1992) craters, or from Cretaceous-Tertiary boundary sites (e.g., Sigurdsson et al., 1991). The glasses are most abundant in the middle section of the Saltpan breccia layer, an observation that has also been made for Ries crater suevite (Stöffler et al., 1977).

Electron microprobe analyses of 25 Saltpan glass fragments revealed that they are mostly homogeneous in composition, except for a few with heterogeneous schlieren. Compositions of glass fragments range from pure SiO_2 glass and SiO_2 glass schlieren in heterogeneous fragments to mixtures derived from melting of silica + alkali feldspar ± plagioclase ± Fe-, Mg-rich minerals. Average glass compositions derived from such mixtures approach the composition of bulk Bushveld granite with reference to SiO_2 and Al_2O_3, but are enriched strongly in Fe and Mg and depleted in Ca and alkali elements (Table 1). It is possible that the glasses are the product of impact melting of Bushveld granite containing similar refractory lithophile element abundances, and some minor admixture of other target rocks (e.g., Karoo metasedimentary rocks).

Sulfide spherules, up to 300 μm in diameter, but mostly smaller than 40 μm, are common in melt and glass fragments and abundant in the fine fraction of the sands. Microprobe analyses showed that they consist mainly of FeS_2, having a constant, nearly stoichiometric Fe:S ratio, but some contain minor SiO_2 (up to 4.5 wt%),

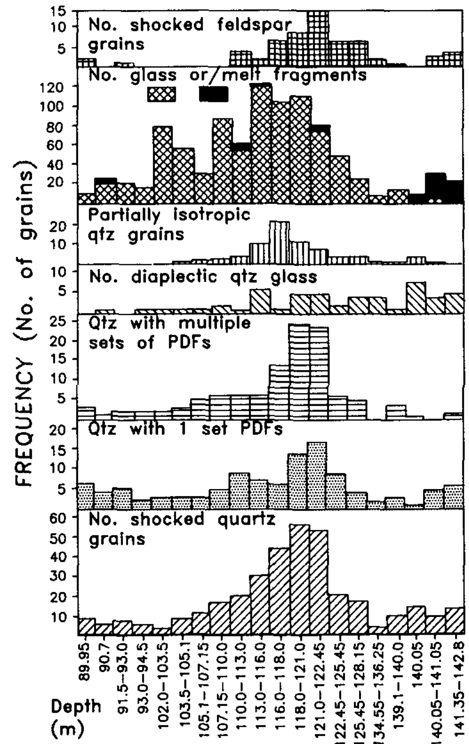

Figure 6. Abundance of shock-metamorphosed minerals and impact glass at various depths in breccia layer. Numbers determined for glass and melt breccia fragments represent minimum figures, because such particles are very abundant in finer, unstudied fractions of suevitic breccia (e.g., in form of tiny glass spherules). PDF = planar deformation feature.

Al_2O_3 (up to 4 wt%), and alkali elements. This suggests that the spherules segregated from a silicate melt, remnants of which are still preserved as microinclusions in pyrite. Several spherules consist of an outer shell of pyrite around an inclusion of silicate in sphere or droplet form, probably representing impact melt.

Basement granite and bulk breccia, agglutinate, glass, and sulfide spherule separates were analyzed by instrumental neutron activation analysis. For Cr, Co, Ni, and Ir (Table 1), average enrichment factors (compared to Bushveld granite) for breccia, agglutinates, and glass, respectively, are: Cr—16, 100, 284; Co—14, 108, 18; Ni—2, 10, 59; Ir—2.9, 3.6, 3.4. Sulfide spherule separates contain up to 100 ppb Ir, compared to <2 ppb background in granite.

CONCLUSIONS

The abundant petrographic evidence for shock metamorphism covering the range of shock pressures between about 15 and 45 GPa in quartz and feldspar minerals and the presence of mineral and rock melts is unequivocal proof for the impact origin of the Pretoria Saltpan crater. On the basis of the presence of shocked mineral fragments, melt breccia, and glass fragments, the granitic sands in the crater interior are classified as an unconsolidated deposit equivalent to suevitic impact breccia. The strong enrichment of glasses and sulfide spherules in siderophile elements and Cr—probably caused by contamination of the breccia by part of the projectile—is regarded as a further indication that the Pretoria Saltpan was formed by meteorite impact.

The excellent preservation state of this young impact crater and its presence in a single crystalline bedrock make the Pretoria Saltpan an ideal subject for further detailed study. Except for the still-debated Vredefort structure, the Pretoria Saltpan is the only confirmed impact structure in South Africa, and one of only two in southern Africa (the other is the barely accessible Roter Kamm crater in the Namib Desert of Namibia). The geologic structure of the Saltpan crater is not fully understood yet, and the possible structural relation between the older intrusive rocks and the impact crater must be further investigated. Geophysical study and drilling will show whether the small circular depression to the south of the Saltpan is indeed a twin crater, a very rare phenomenon in the terrestrial impact cratering record.

A first-order observation from published impact structure tabulations (e.g., Grieve, 1982) is that many small (<3.5 km diameter) craters of simple bowl shape are listed, but that only a few of these were formed in crystalline bedrock, like the Pretoria Saltpan crater. Detailed drilling information on internal structure and stratigraphy of these craters is available only for the Brent (3.8 km diameter) and West Hawk Lake (2.44 km diameter) craters, formed in mainly felsic rock, and the Lonar crater (1.71 km diameter), formed in basaltic country rock. Grieve et al. (1989) established for the Brent and West Hawk Lake craters that, on the basis of crater geometrical constraints, it is possible to predict with reasonable precision the volumes of breccia lenses within impact structures. However, they also showed that a 10% increase of the crater diameter can result in an increase up to 200% of the calculated breccia volume. In the Saltpan crater, which is significantly smaller (1.13 km diameter) than the Brent and West Hawk Lake craters, the ratio of true depth (base of breccia layer) to (estimated) original diameter (~800 m; Fig. 4) conforms well with values for other bowl-shaped structures, but the Saltpan breccia lens is much thinner than those in other craters. This observation is interpreted as being primarily a result of the much smaller size of the Saltpan crater, in agreement with data listed by Grieve et al. (1989, Table 3) for other small impact structures. This, and the fact that the Saltpan crater was basically formed in one rock type (coarse-grained granite), could also be the reason for the apparent development of a small volume of impact melt. In comparison to the Brent and West Hawk Lake craters, which are ca. 450 and 100 Ma, respectively, the Saltpan crater is very young, ca. 200 ka. This low age, the lack of an appreciable melt component in the crater fill, and the limited alteration (confined to narrow zones in the breccia layer) may be the reasons why the Saltpan breccia is unconsolidated and does not contain a matrix comparable to that of regular suevite (mixture of fine-grained clastic and alteration-derived argillaceous phases). Another difference between the Saltpan and other bowl-shaped craters (except for the 2.5-km-wide Roter Kamm crater in Namibia) is the complete lack of shock-metamorphic effects in the crater basement below the breccia layer and in the crater rim. Although no definite explanation for this observation can be given at this stage, one could assume that this is also the likely result of a much less energetic impact than those that formed larger structures.

This comparison between the Saltpan crater and other bowl-shaped structures demonstrates that our understanding of the cratering process and resulting crater geometries and distribution of shock deformation is still incomplete, thus necessitating further research, even on simple bowl-shaped structures. Another reason for ongoing geological interest in young, well-preserved impact structures is the recent recognition that the fill of such structures may yield extensive Quaternary paleoenvironmental records. The Saltpan study has already contributed to an improved understanding of climatic conditions in the Southern Hemisphere during the late Pleistocene, and the New Quebec impact structure may provide a sedimentary record for the Pleistocene of northern Canada (Grieve et al., 1991).

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