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Hydrological impact of the Pretoria Saltpan crater, South Africa

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Abstract—The crater known as the Pretoria Saltpan was caused by the impact of a meteorite approximately 220,000 years ago. Because the bottom of the crater floor is below the local water table, groundwater has flowed into a semi-permanent lake since the formation of the crater. A distinction is made between the undisturbed hydrology of the crater system, and the hydrology of the crater after human interference. Estimated annual evaporation (2350 mm) currently far exceeds annual rainfall in the area (614 mm). Simple calculations show that 143,000 $m^3 yr^{-1}$ flow into the crater by overland flow from the crater wall, as well as direct precipitation onto the crater lake surface, whilst 178,000 $m^3 yr^{-1}$ are lost from the lake surface by evaporation. Approximately 35,000 $m^3 yr^{-1}$ of lake water is replaced by groundwater seepage, currently through artesian boreholes. The crater has therefore been acting as a groundwater pump. The total amount of groundwater lost over the nominal age of the crater through evaporation is approximately 7.6 km^3. Oxygen and hydrogen isotope analyses of the pan brine and adjacent groundwater shows that some brine has escaped from the crater, possibly contributing to the poor water quality of the area. Copyright © 1996 Elsevier Science Ltd.

Résumé—Le cratère connu sous le nom de Pretoria Saltpan ('cuvette saline de Pretoria') est dû à un impact météorique datant d'environ 220.000 ans. Le fond du cratère se trouvant sous le niveau de la nappe phréatique locale, il s'y est formé depuis l'impact un lac semi-permanent. Il y a lieu de faire une distinction entre l'hydrologie non-perturbée de l'ensemble du cratère et celle due à l'interférence humaine. Dans la région les estimations d'évaporation annuelle (2350 mm) dépassent de loin les précipitations annuelles (614 mm). De simples calculs indiquent que 143.000 m^3/an d'eau, soit en provenance des parois du cratère convergent par flux de surface dans celui-ci, soit s'y ajoutent par précipitation directe sur sa surface, tandis que 178.000 m^3/an sont perdus par évaporation à partir de la surface du lac. Quelque 35.000 m^3/an d'eau lacustre sont remplacés par remontée de la nappe grâce à la présence de puits de forage artésiens. Ainsi le cratère fonctionne à la manière d'une pompe affectant la nappe phréatique. La quantité totale d'eau provenant de la nappe, perdue par évaporation en tenant compte de l'âge nominal du cratère, est d'environ 7.6 km^3. L'analyse des isotopes d'oxygène et d'hydrogène des eaux salées de la cuvette ainsi que de la nappe phréatique environnante montre qu'une certaine quantité d'eau salée a percolé hors du cratère, rendant ainsi probablement compte de la qualité médiocre des eaux de la région. Copyright © 1996 Elsevier Science Ltd.

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INTRODUCTION

The recent impact of comet Schumacher-Levy 9 with Jupiter has highlighted the role of meteorite impacts as agents in the formation of planetary surfaces. The Chicxulub impact crater of the Yucatan Peninsula, of Cretaceous-Tertiary boundary age, has been linked to present day hydrological features, showing that impact craters can have a long lasting effect on surface water and groundwater (Perry *et al.*, 1995). In this paper we show that a more recent impact crater in South Africa has had a lasting effect on groundwater quality. The Pretoria Saltpan impact crater is located 40 km northwest of Pretoria and consists of a ring of low hills with a diameter of 1.1 km, surrounding a depressed circular floor containing a small lake (Fig. 1). The structure had previously been ascribed a volcanic origin (Wagner, 1920, 1922;

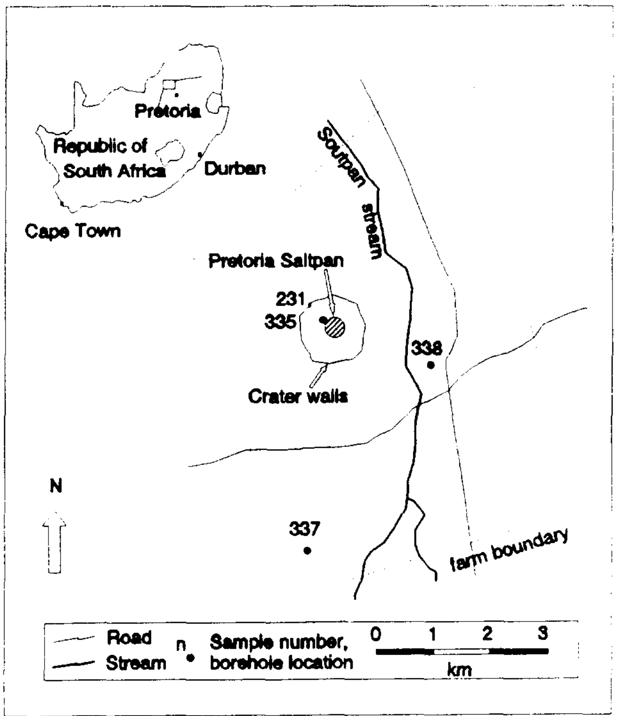

Figure 1. Locations of the Pretoria Saltpan and position of sampling points referred to in the text.

Feuchtwanger, 1973; Fudali *et al.*, 1973), before a borehole penetrating the structure gave unambiguous evidence for a meteoritic origin (Reimold *et al.*, 1991, 1992). Further studies have refined knowledge of the structure of the crater and the nature of the colliding bolide (Brandt, 1994; Koeberl *et al.*, 1994). Brandt and Reimold (1995) showed that the impact crater is formed in an area of Nebo granite, which had been, before the impact, intruded by various alkaline bodies including carbonatite, trachyte and lamprophyre. Partridge *et al.* (1993) gave a detailed account of the stratigraphy of the borehole, which showed the crater had been excavated to a depth of 151 m below the present floor, had been infilled by granitic breccia to a depth of 90 m, and that the remaining crater infill was a mixture of fine-grained clastic sediments and evaporite minerals. A detailed study of the crater lake was undertaken by Ashton and Schoeman (1983), including chemistry of the lake brines and the present water balance for the structure. Studies of the diatom flora of the area have been extensive (Schoeman and Ashton, 1982,1983; Schoeman *et al.*, 1984). The composition of the groundwater in the area has been studied by Bond (1946) and Schoeman and Ashton (1982), who found it to be typical of granitic terrains. The purpose of this paper is to discuss the hydrological repercussions of the formation of the crater. A historical water balance is proposed, and the ionic and isotopic composition of groundwaters have been measured and are used to show the influence of the impact structure on the groundwater in the vicinity.

CONCEPTUAL MODEL

A conceptual model of the hydrological systems set up by the creation of the crater is shown graphically in Fig. 2. After impact of the bolide, rainwater and groundwater rapidly floods the crater. The lake surface is lowered by evaporation, and groundwater seeps into the crater to maintain an equilibrium. The lakewater, which is a mix of fresh groundwater in chemical equilibrium with the Nebo granite and evaporated lakewater, is continually concentrated by evaporation, resulting in the precipitation of supersaturated minerals. The lakewater becomes isotopically fractionated in relation to the inflowing rain and groundwater. In arid times, evaporation completely outstrips groundwater and rainwater inflow, reducing the lake volume and generating dense, heavy-isotope enriched brines. When rainfall and groundwater inflow increase, the dense brines are left at the bottom of the lake and can then escape from the bottom of the crater by density driven flow. As the lake volume is reduced by collapse of the crater sides and precipitation of minerals from solution, the lake becomes more susceptible to evaporation and the generation of brines. The low porosity of the surrounding granite ensures that groundwater level increases are greater after rainfall than the increase in the level of the lake.

WATER BALANCE

A water balance equation for the Pretoria Saltpan (or just 'Saltpan') has been proposed by Ashton and Schoeman (1983):

$$\Delta V = V_i + V_p + V_r - V_e, \qquad (1)$$

where ΔV is change in lake volume, V_i is groundwater input, V_p is direct precipitation on the lake surface, V_r is surface runoff from the surrounding crater walls and V_e is evaporation. They used this equation and measurements of ΔV, V_i, rainfall and evaporation to estimate V_r at 18%.

Equation 1 can be used as a basis for calculating groundwater lost to the atmosphere since the creation of the crater. It is assumed that, since impact, the lake surface has been at approximately the level of the water table (*i.e.* no change in lake volume over geological time, or $\Delta V \approx 0$). Although Partridge *et al.* (1993) showed from the study of microfossils contained in a core taken from the crater that the area has been subject to fluctuations in aridity (rainfall and evaporation), the volume of groundwater available for inflow into the crater is so

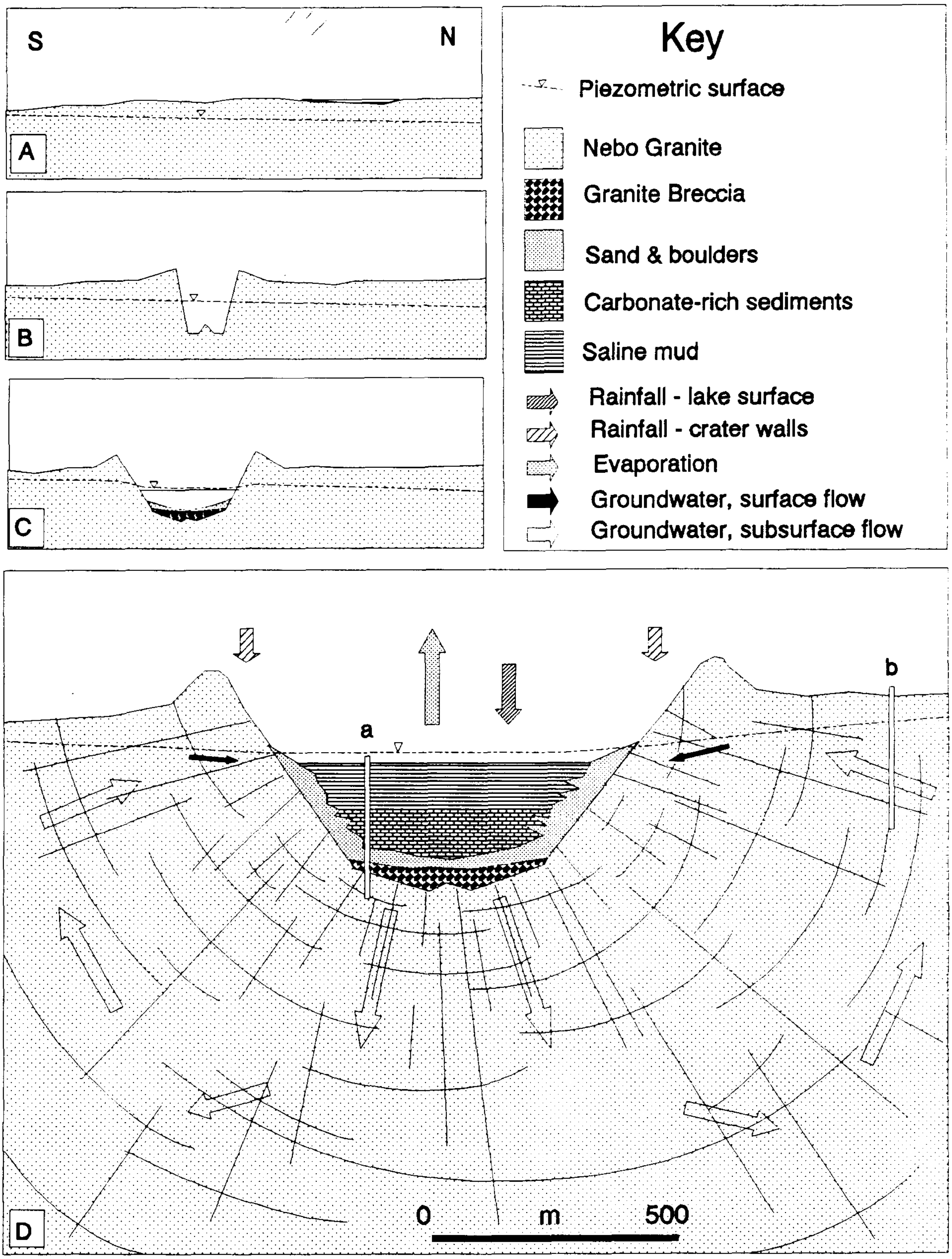

Figure 2. A conceptual model of the hydrological systems set up by the saltpan meteorite impact. A - Before impact: Nebo granite with subdued topography and water table sloping gently to the north. B - Crater floods immediately after formation. C - Partial collapse of crater sidewalls, onset of clastic sedimentation, evaporation commences and piezometric surface is lowered in vicinity. D: Evaporation exceeds direct rainfall and runoff. Groundwater inflow through peripheral springs (currently artesian borehole). Possible exit of crater brines with evaporitic signature through fractured floor rocks, mixed with incoming fresh groundwater to give Nebo granite groundwater-brine mixture up to 1000 m away. (a) location of artesian borehole and (b) location of Mr Mon's borehole (no. 338).

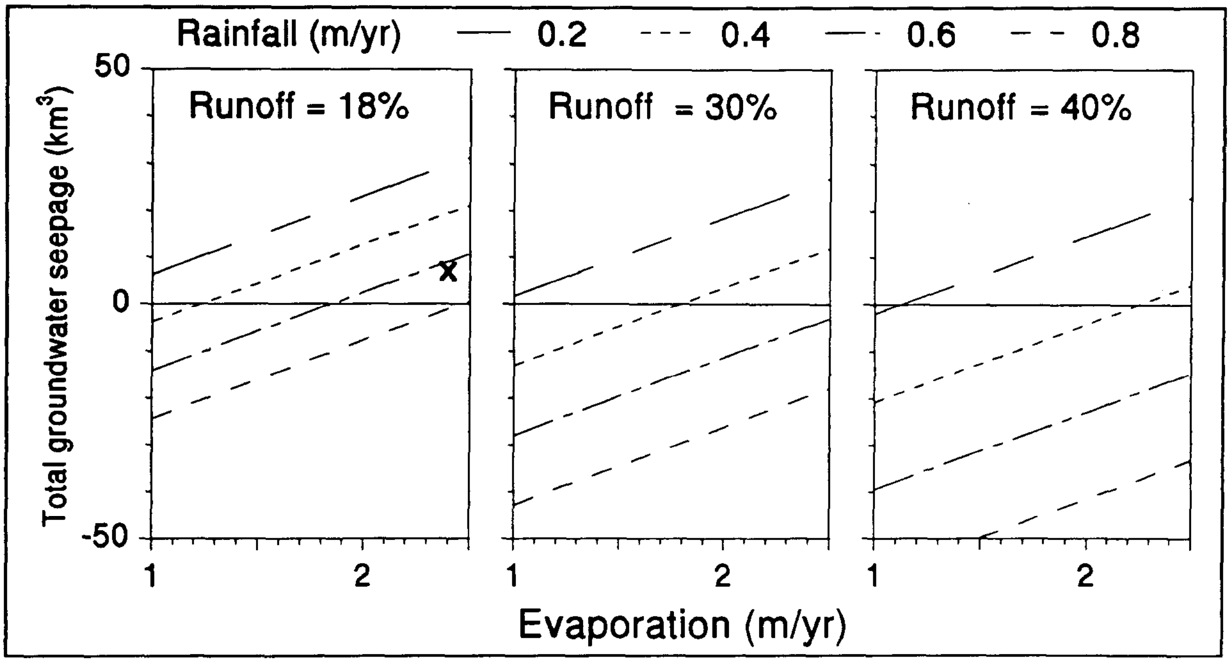

Figure 3. Results of applying equation 2 to the Saltpan crater, showing the total groundwater flows in to and out of the crater over 220,000 years. The three graphs show calculated groundwater flows, assuming runoff is 18%, 30% and 40% of rainfall, with the remainder being lost to evaporation. The figure of 18% runoff is that calculated for the Pretoria Saltpan, although other salt lakes receive higher percentages from runoff (Ashton and Schoeman, 1983). The mean rainfall and evaporation figures over the last 220,000 years are not known, and are not likely to coincide with the means calculated from current weather data. Because of this, equation 2 has been used to calculate the flows into and out of the crater, assuming varying rainfall (0.2 to 0.8 meters per year) and evaporation (between 1 and 2.5 meters per year). Positive groundwater flows indicate groundwater seepage into the crater; negative flows indicate that it exits. 'X' marks the present climatic conditions.

large that it is an acceptable assumption that groundwater has continuously flowed into the crater, even during arid episodes when water tables are lowered. The lake surface would have been severely depressed during xeric episodes, enough to evaporate to dryness at times, but even then it is likely that groundwater has flowed in to compensate for the evaporation deficit. Equation 1 can be therefore be rewritten as:

$$V_i = V_e + V_s - V_p - V_r \qquad (2)$$

The term V_s is introduced to represent 'subflow', the outflow of dense brine from the crater. This becomes a necessary concept after an examination of the isotope results of the surrounding groundwater (see below).

Making the simplifying assumption that the mean evaporation and rainfall in the area over the life of the crater is equivalent to the present mean, it becomes possible to calculate a mean groundwater inflow per annum, and thence the total groundwater flow to the crater since inception. Taking a value of V_r of 18% of the rainfall, a mean lake area of 75,700 m^2, total crater area of 950,000 m^2 and evaporation of 2350 mm (calculated by triangulation from surrounding evaporation pans, using Weather Bureau raw data) and mean annual precipitation (MAP) of 614 mm, a groundwater inflow of 35,000 m^3 per annum is calculated. Explicitly, this figure is calculated by first multiplying the area of the crater rim (crater area-lake area = 874,300 m^2) by the MAP (0.614 m yr^{-1}) and the assumed percentage of runoff (18%) to give the crater runoff per annum (96,630 $m^3\ yr^{-1}$). The total rainwater inflow to the lake surface is calculated by the addition of direct precipitation to the lake surface (lake area x MAP = 46,480 $m^3 yr^{-1}$) to the crater runoff, which gives 143,110 $m^3 yr^{-1}$. Evaporation from the lake surface is equivalent to the lake area (75,700 m^2) multiplied by the mean annual evaporation (2.35 m yr^{-1}) to give 177,895 $m^3 yr^{-1}$. According to equation 2, the total rainwater inflow (143,110 $m^3\ yr^{-1}$) less the evaporation (177,895 $m^3\ yr^{-1}$) gives the inflow of groundwater (34,790 $m^3\ yr^{-1}$).

If the age of the crater is 220,000 years (Partridge *et al.*, 1993), then the total groundwater inflow has been approximately 7.6 km^3. This oversimplifies the system, however. The palaeoclimate in the area has fluctuated significantly over the life of the crater (Partridge *et al.*, 1993) and so a series of values for average rainfall, evaporation and V_r have been used in equation 2 to produce the curves in Fig. 3. Given

Table 1. Chemical analyses of groundwater from the vicinity of the Saltpan (map area 2528AC, n = 26), and from a control area of Nebo Granite 100 km from the crater (map area 2527AD, n = 24)

	Ca	Cl	F	Mg	NO_3-N	K	Na	SO_4	T.Alk	pH
2528AC: mean	47.1	37.7	2.7	12.8	608.0	4.3	77.2	8.5	211.8	7.2
s.d.	36.9	30.9	4.7	9.3	1851.2	1.7	81.3	8.2	82.0	0.4
2527AD: mean	41.2	26.8	1.1	22.0	9.0	2.8	42.3	16.9	-	7.3
s.d.	21.0	33.0	0.8	21.6	10.4	3.4	31.9	19.6	-	0.7

Concentrations are in mg l^{-1}. - not determined in this and the following tables.

Table 2. Chemical analyses of groundwater from the immediate vicinity of the Saltpan

Number and name	Ca	Cl	F	Mg	NO_3-N	K	Na	SO_4	T.Alk	pH
230: Saltpan brine	33.8	16000	195.0	2.4	51.7	73.0	14000	129	-	10
231: Artesian borehole #1	18.1	-	7.4	6.0	-	29.1	2560	-	-	9.1
335: Artesian borehole #2	8.5	1550	7.6	1.5	0.0	9.7	1050	0	259	8.2
337: Museum borehole	16.6	6.4	1.1	2.1	14.1	2.7	30.8	0	75	7
338: Mr Mon's borehole	26.1	141	1.9	9.9	27.6	5.5	114.1	26.9	187	7

Concentrations are in mg l^{-1}.

that an ice-age was in progress over most of the life of the crater, mean evaporation and rainfall over the lifetime of the crater will be lower than the present means. The present rainfall, evaporation and V_r values show that groundwater is currently flowing into the crater to be lost through evaporation into the atmosphere.

METHODOLOGY

Groundwater samples were collected from boreholes via engines in June 1993 and June/July 1994, following the guidelines of Weaver (1992). The samples were collected in pre-contaminated 125 ml plastic bottles. Temperature, pH and methyl orange alkalinity were measured at the well head. F^- concentration was measured within 8 hours of sampling using an Orion F^- Ion Selective Electrode (Frant and Ross, 1966) and a Corning 255 digital millivolt meter. A total ionic strength adjustment buffer containing cyclohexylene diamine tetraacetic acid as a complexing agent was used throughout (Harwood, 1969; McCaffrey, 1994). High Performance Ion Chromatography was used to determine major anion and cation concentrations, using artificial standards with ionic proportions similar to that found in the samples.

Samples of water from all boreholes surrounding the Saltpan, and from several boreholes in Nebo granite well away from the Saltpan, were analysed for the isotopes of hydrogen and oxygen. Salts were removed from the Saltpan brine sample by cryogenic vacuum distillation, thereby avoiding fractionation. The preparation technique used for oxygen was that of Socki *et al.* (1992). Hydrogen isotope data were obtained by the method of Venneman and O'Neil (1993). Mass spectrometric measurements were made with a Finnegan MAT 252 mass spectrometer. The stable isotope data is expressed in δ notation:

$$\delta = 1000 \times \frac{R_{sample}}{R_{standard}} - 1 \qquad (3)$$

where R = $^{18}O/^{16}O$ or D/H. Values are expressed relative to the SMOW scale to which they were calibrated using an internal water standard of known δD and $\delta^{18}O$ value. Following the recommendation of Coplen (1988), we have normalized our data so that the SLAP standard gives a $\delta^{18}O$ value of -55.5‰ and a δD value of -428‰ relative to SMOW.

IONIC ANALYSIS RESULTS

If the conceptual model is correct, it might be found that brines seeping from the bottom of the crater can be sampled from boreholes surrounding the crater. To test this theory, major ions have been determined in groundwater samples from the vicinity of the crater, and from an area of Nebo granite 100 km from the crater. The results are presented in Table 1. The means of each ionic concentration are similar, showing that the two areas of the Nebo granite have similar groundwater compositions. The only notable exception is NO_3, which has a very high mean concentration in map area 2528AC. Pit latrines are the usual method of the disposal of human waste in the area, and so the high nitrate concentrations are probably anthropogenic. The conclusion from these data, therefore, is that the crater has not significantly affected the groundwater chemistry of the surrounding area.

Table 3. Isotope analyses for groundwater and surface brine from the vicinity of the Pretoria saltpan. The first two analyses are for 'pristine' Nebo Granite groundwater, located 10 km from the crater. See text for details of notation and analysis.

LOCATION	δ^2H	$\delta^{18}O$
Theledi's Farm borehole	-22	-4.6
Stinkwater (borehole)	-27	-4.2
Surface brine	10	0.1
231: Artesian borehole	-27	-4.3
335: Artesian borehole	-28	-4.5
337: Museum borehole	-30	-4.6
338: Mr Mon's borehole	-10	-2.0

Groundwater from four boreholes in the immediate vicinity of the crater, as well as the brine currently found in the crater, have also been analysed, and the results are shown in Table 2. Unfortunately few boreholes exist in the area. The ionic analysis of the brine shows results in the same order of magnitude as those of Ashton and Schoeman (1983), apart from the determination of F. Given that the samples were taken 12 years apart, and that the evaporation-precipitation balance is likely to have been uneven over that time, the difference in major ion chemistry is acceptable. However, the F concentration of 0.3 mg l^{-1} determined by these workers is almost certainly incorrect, since the most recent analysis has determined F^- concentration at 195 mg l^{-1}.

Two artesian boreholes have been drilled into the centre of the crater, and apparently tap groundwater under pressure in the sandy aquifer between 90 and 151 m depth (Partridge *et al.*, 1993). The analyses (nos 231 and 335) show that this groundwater is low in Ca and Mg, but very enriched in Na, K and Cl and high in F. Partridge *et al.* state that these waters have ionic concentrations in the same proportions as the current lake water and local groundwater: the current analyses do not support this conclusion. Rather, the groundwater of the two central boreholes are enriched in Na, K, and Cl with respect to Nebo granite groundwater. These artesian groundwaters would, at first inspection, be the result of evaporation of the local groundwater, with resultant precipitation of $CaCO_3$ and $CaMg(CO_3)_2$ and concentration of more conservative ions such as Na^+ and K^+. However, the isotope results do not support this conclusion. The inverse is found when considering a sample of groundwater (no. 338) taken from a borehole at Mr Mon's trading store, 1 km to the east of the crater. Here the groundwater is similar to other Nebo granite groundwaters, but with increased Cl, Na and sulphate. The chemical analysis of the water suggests that evaporation has occurred, since the ionic concentrations of the conservative ions are higher than the 'unevaporated' Nebo granite groundwater located 100 km from the crater. The isotope results for this groundwater sample confirm either that it has been evaporated, or that it has mixed with water which has been evaporated (see below). The other groundwater sample (no. 337) taken from the vicinity of the crater, but positioned 'upstream' in the regional groundwater flow, shows no evidence of evaporation, either from the chemical or isotopic analyses.

ISOTOPE RESULTS

The results are shown in Table 3. It is apparent that pristine, unevaporated groundwater hosted in the Nebo granite bedrock has a δD value of around -27‰ ($n=5, 1\sigma = 2.6$) and a $\delta^{18}O$ value of approximately -4.5‰ ($n=5$, $1\sigma = 0.18$). The Saltpan brine has been subject to evaporation for a period of only 60 years (Ashton and Schoeman, 1983). However, the surface brine has high $\delta^{18}O$ and δD values (+0.1, +10 ‰ respectively). These high values can most easily be explained by evaporation of water having isotope ratios close to the values seen in groundwater in the region. Evaporation is a fairly complex process controlled by a number of variables (e.g. Merlivat and Jouzel, 1979). It is necessary to consider both the kinetically controlled evaporative loss of water molecules and the equilibrium isotope exchange of water vapour and the liquid surface (e.g. Welham, 1987). Figure 4 shows the trend for saline groundwaters of the Kalahari, which are interpreted as an evaporation trend (Verhagen, 1984). The Kalahari trend has a less steep gradient on Fig. 4 than the meteoric water line, and this type of array is characteristic of regions with low relative humidity and high daily temperatures (*e.g.* Welham, 1987, p. 141). That the surface brine at the Saltpan is close to the meteoric water line is indicative that the evaporation must have taken place in conditions of very high relative humidity. Although high humidity is not a general feature of the Pretoria region, the fact that the evaporating Saltpan was at the bottom of a deep crater would have minimised the dissipation of water vapour by the wind, enabling continual exchange between vapour and liquid at the air-water interface. Simple calculations assuming equilibrium Rayleigh separation of water and vapour indicate that about 40-50% evaporation of water having a $\delta^{18}O$ and δD values of -4.5‰ and -30‰ respectively (typical Nebo granite-hosted groundwater) could produce the isotope composition of the Saltpan brine at an average temperature of 30°C.

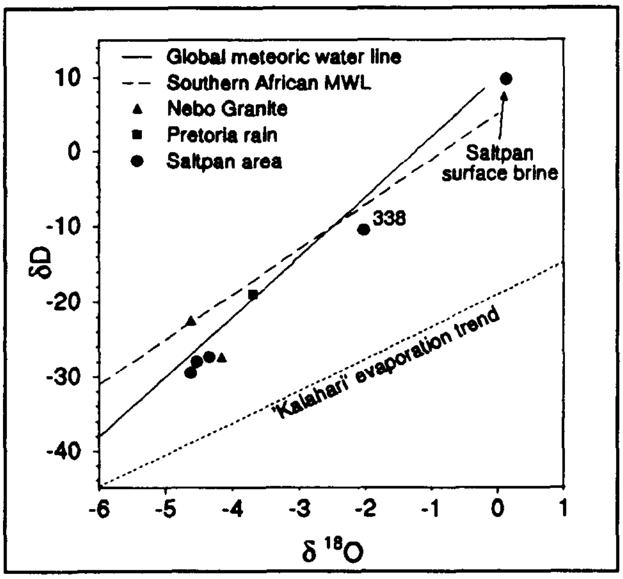

Figure 4. Oxygen and hydrogen isotope variation in surface brine from the Pretoria saltpan, from groundwater in the vicinity, and from groundwater hosted in Nebo granite but far from the crater. Global meteoric water line (MWL) from Craig (1961); Southern African MWL from Mazor and Verhagen, (1983); Evaporation trend of the Kalahari groundwaters from Verhagen (1984).

Of note are the isotope values in the groundwater intersected at Mr Mon's Trading store (site 338). Both δD and $\delta^{18}O$ show a distinct evaporative component. It is suggested either that this groundwater is a mixture of pristine Nebo granite groundwater and Saltpan brine, or that it is a less evaporated brine. Either of these eventualities justify the addition of the term V_s ('subflow') to equation 2. An objection to the contention that brine is leaving the crater is that it would have to move against groundwater flow into the crater. One solution to this problem could be that dense brine is exiting the crater through the fractured rock at its base, avoiding the lateral groundwater flow closer to the water table. This movement would be topologically similar to the model proposed by Gieske (1995) for certain islands in the Okavango delta of Botswana. Dense brines generated by evapotranspiration of fresh water exit downwards from the centre of islands, driven by density-dependant flow. These brines can subsequently mix with inflowing fresh water in the periphery of each island system.

CONCLUSIONS

The Pretoria Saltpan impact crater has affected the chemistry and isotope composition of groundwater in the area. The current understanding of the palaeoclimatology of the region is not specific enough to allow accurate modelling of the crater-groundwater system, but work currently being done may eventually allow this (Partridge, 1995, *pers. comm.*). If it is assumed that current conditions approximate conditions extant over the lifetime of the crater, then a large amount of groundwater has been evaporated from the crater, but this is a crude approximation of reality. Brines are forming in the crater through evaporation of inflowing groundwater and rainwater, and are leaving the crater by density-driven flow. It is suggested that similar processes are operating at impact sites in semi-arid regions around the world, wherever the crater penetrates the local groundwater table. Several suitable craters exist in Africa, e.g. Bosumtwi in Ghana (Koeberl, 1994). Isotopic and major element studies of groundwater in and around such craters should confirm this assertion.

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