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ORBITAL FORCING OF CLIMATE OVER SOUTH AFRICA: A 200,000-YEAR RAINFALL RECORD FROM THE PRETORIA SALTPAN

T. C. PARTRIDGE,[*] P. B. DEMENOCAL,[†] S. A. LORENTZ,[‡] M. J. PAIKER[§] and J. C. VOGEL[¶]
[*]*Climatology Research Group, University of the Witwatersrand, Johannesburg, South Africa*
(E-mail: 141tcp@cosmos.wits.ac.za)
[†]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, U.S.A.*
[‡]*Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa*
[§]*Department of Statistics and Actuarial Science, University of the Witwatersrand, Johannesburg, South Africa*
[¶]*Quaternary Dating Research Unit, CSIR, Pretoria, South Africa*

Abstract — Late Pleistocene variations in rainfall in subtropical southern African are estimated from sediments preserved in the Pretoria Saltpan, a 200 000 year-old closed-basin crater lake on the interior plateau of South Africa. We show that South African summer rainfall covaried with changes in southern hemisphere summer insolation resulting from orbital precession. As predicted by orbital precession geometry (Berger, 1978), this South African record is out of phase with North African palaeomonsoon indices (Street and Grove, 1979; Rossignol-Strick, 1983; McIntyre *et al*., 1989); the amplitude of the rainfall response to insolation forcing agrees with climate model estimates (Prell and Kutzbach, 1987). These results document the importance of direct orbital insolation forcing on both subtropical North and South African climate as well as the predicted antiphase sensitivity to precessional insolation forcing. © 1998 Elsevier Science Ltd. All rights reserved

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Palaeoclimate records from the northern hemisphere subtropics demonstrate that earth orbital precession was a dominant factor regulating Pleistocene variations in West African and Indian monsoonal climate (Street and Grove, 1979; Rossignol-Strick, 1983; Pokras and Mix, 1987; Prell and Van Campo, 1986; Prell and Kutzbach, 1987; McIntyre *et al.*, 1989; Clemens *et al.*, 1991). Gravitational interactions between the earth, sun, moon, and more massive planets cause the Earth's rotational axis to precess at 23,000-year and 19,000-year periods (Berger, 1978), changing the season during which the Earth passes closest to the sun (perihelion) and, consequently, the amount of summer season insolation.

Strongly seasonal climates develop from the differing heat capacities of land and ocean (land surfaces can be heated much more readily than the ~100 m surface mixed layer of the ocean, so precessional variations in summer insolation affect circulation and rainfall (Kutzbach, 1981; Prell and Kutzbach, 1987)). Pleistocene records of African and Indian climate vary primarily at precessional periods (Pokras and Mix, 1985; Prell and Van Campo, 1986; Prell and Kutzbach, 1987; Clemens *et al.*, 1991) and are in phase with calculated variations in summer season insolation for the northern subtropics (Street and Grove, 1979; Rossignol-Strick, 1983; McIntyre *et al.*, 1989).

Orbital precession geometry predicts that changes in summer season insolation should be antiphase between hemispheres. For example, North African summers were 8% more radiant 10,000 years ago whereas South African summers were 8% less radiant (Berger, 1978). Hence, the Pleistocene palaeoclimate record of South Africa provides a key test of this subtropical climate change mechanism. The sedimentary record of the Pretoria Saltpan is one of the few suitably long and continuous palaeoclimate records from the southern hemisphere which can be used to document this phenomenon.

SOUTH AFRICAN CLIMATE AND THE PRETORIA SALTPAN

South African interior rainfall occurs during the austral summer months (DJF) and is most strongly influenced by tropical northerly airflow, which is enhanced by periodic coupling with temperate troughs (D'Abreton and Tyson, 1994). Summer heating establishes a persistent cyclonic low-pressure cell over Zaire which draws moisture from the western Indian Ocean into the continental interior, from where it is advected southwards over southern Africa. The region becomes cool and dry during the winter months (JJA) as the land surface cools relative to the oceans and a broad anticyclonic (high-pressure) circulation prevails. Interannual variations in South African rainfall have been linked to the Southern Oscillation–El Niño changes in western Indian Ocean

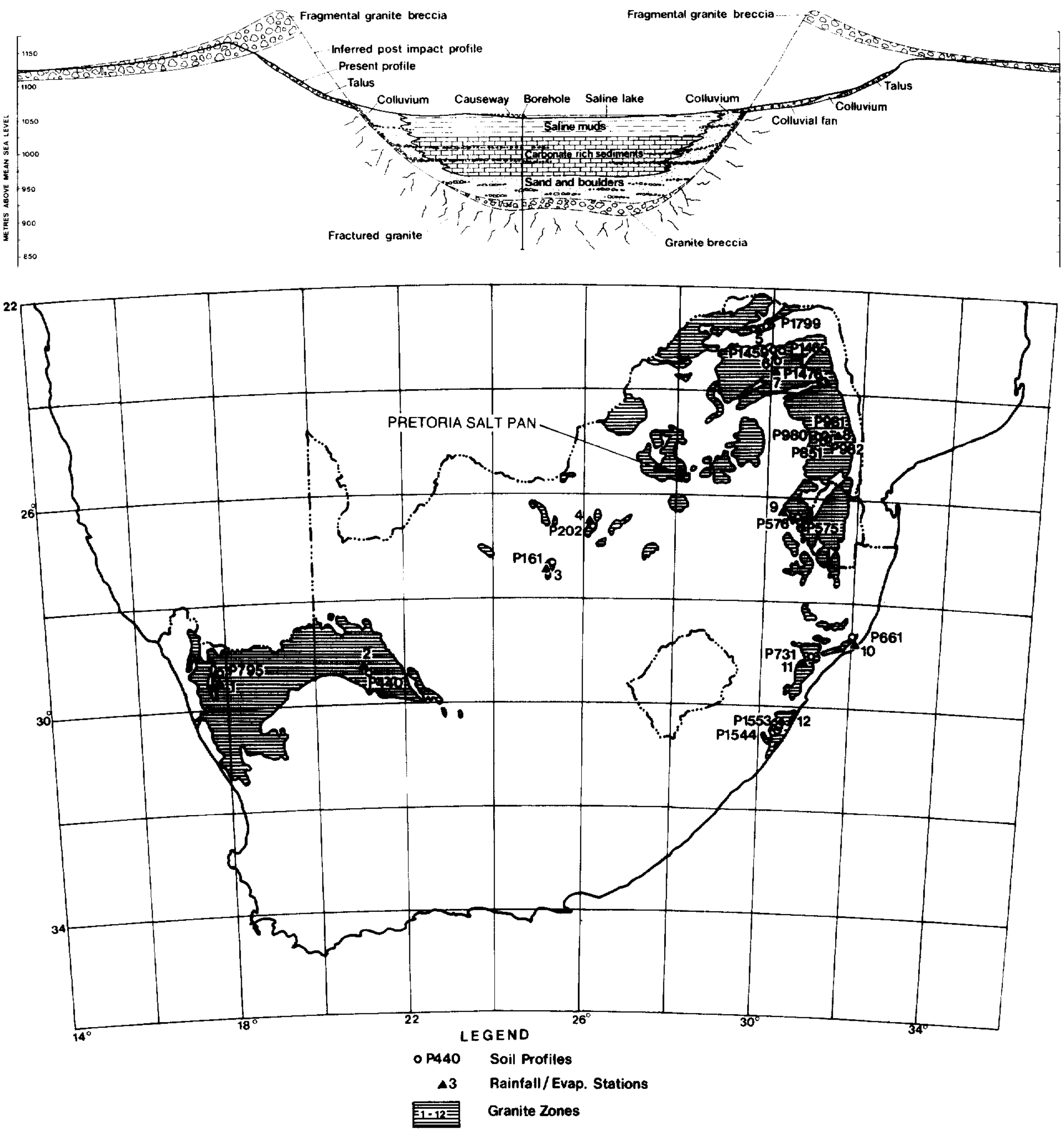

FIG. 1. Pretoria Saltpan site location, soil sample locations and schematic cross-section.

sea-surface temperatures (Cane *et al.*, 1994; D'Abreton and Tyson, 1994; Mason, 1994).

The Pretoria Saltpan is a closed-basin crater (maar) lake 1.13 km in diameter which is on the interior plateau of South Africa, 40 km NNW of Pretoria (Partridge *et al.*, 1993; Fig. 1). The present climate is subtropical with hot, rainy (630 mm/year) summers and cool, dry winters. The deciduous savanna vegetation of the environs is typical of large areas in the north-eastern hinterland of South Africa. The hydrologic balance of the present lake is such that an annual evaporative loss of 175,000 m^3 is balanced by 48,000 m^3 of rainfall and 100,000 m^3 of crater-wall runoff; an estimated 26,000 m^3 enters from artesian flow (Ashton and Schoeman, 1983). A shallow (3 m) alkaline (pH ~10) lake of ~7500 m^2 occupies the present crater. The lake is only some 300 m in diameter, and has a surface area less than 8% that of the surrounding crater basin. Hence, the grain size distribution of the sediments trapped in the lake is very closely related to that of soils generated by weathering of the crater sides, and owes little to lateral sedimentary sorting within the lake or to the influence of winds and currents.

The Saltpan basin was formed by a meteorite impact cratering event dated near 220,000±52,000 years from fission-track analysis of basal impact glasses (Reimold *et al.*, 1991; Partridge *et al.*, 1993). In 1988–1989, a borehole was sunk into the centre of the Pretoria Saltpan (Fig. 1) to investigate the palaeoenvironmental record of the saltpan lake sediments and the timing and cause of the cratering event (Partridge *et al.*, 1993). The hole

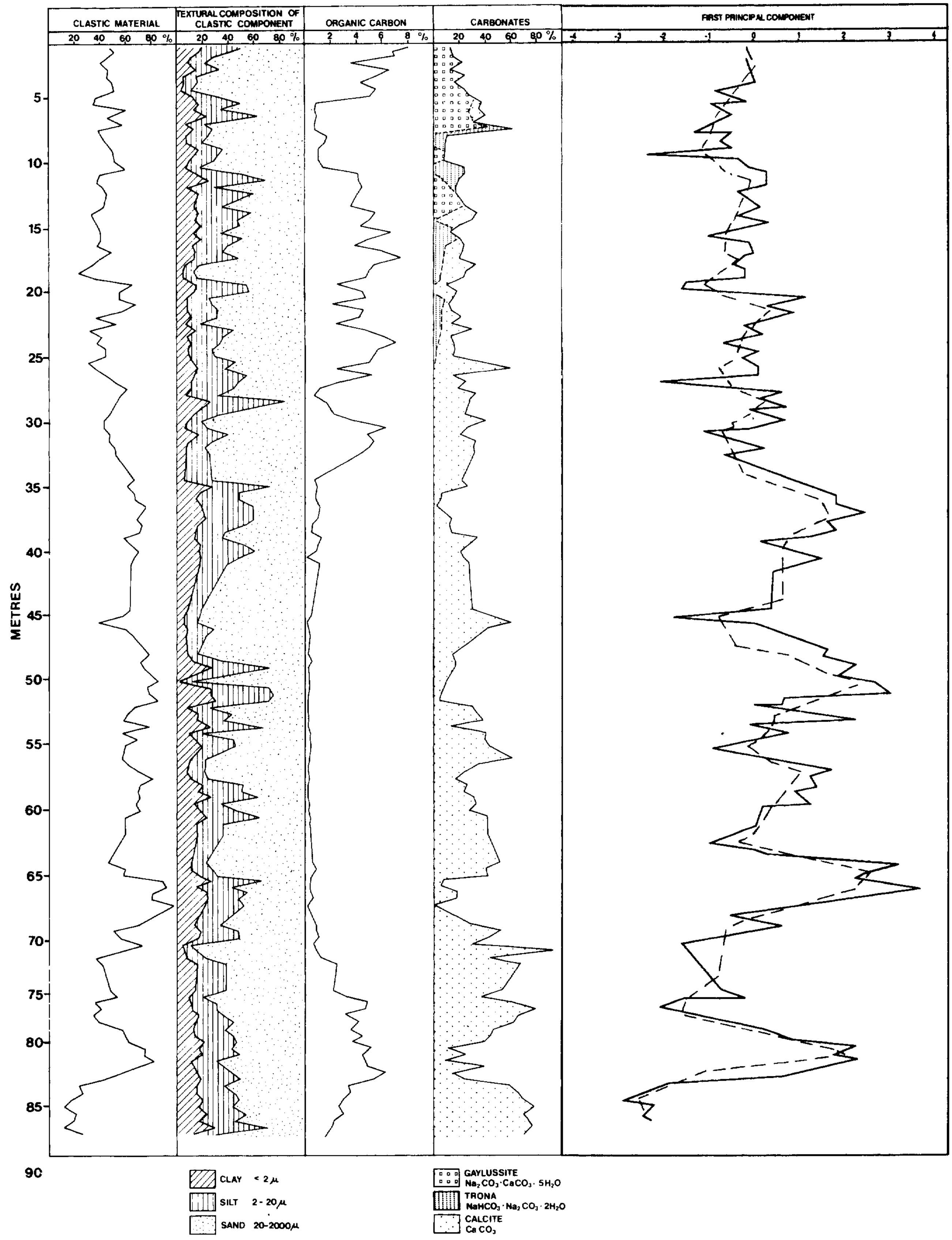

FIG. 2. Major sedimentological components of the lacustrine succession and the first eigenvector (61% of total variance) from a principal component analysis of the Pretoria Saltpan textural and compositional data (PCI). The broken line shows the results of smoothing the eigenvector data using a 5-point moving average.

penetrated 90 m of lacustrine sediments; coarse sand, gravel and boulders occurred between 90–151 m, and recovery below 151 m consisted of fractured Nebo Granite of the Bushveld Igneous Complex. The sediments below 90 m exhibit numerous impact-related phenomena, including planar deformation features in quartz and feldspar grains, diaplectic quartz glass and melt-breccia fragments. This basal coarse-grained detritus is, in fact, a suevitic impact breccia associated with the formation of the crater (Storzer *et al.*, 1993).

THE PALAEOCLIMATE RECORD OF THE PRETORIA SALTPAN

The rimmed Saltpan basin appears to have acted as a closed hydrographic system ('amplifier lake'; Street and Grove, 1979) which recorded past variations in regional precipitation. The 90 m succession of lacustrine sediments in the Pretoria Saltpan consists of an evaporite-rich depositional sequence with lithologic evidence of alternatively wetter and drier conditions (Fig. 2). The onset of lacustrine deposition near 200 000 years ago is documented by the deposition of alternating units of finer, carbonate-rich (micritic) sediment and coarser terrigenous clay and silt (Partridge *et al.*, 1993). The uppermost 40 m of the sequence contains increasingly large percentages of evaporite minerals (halite, trona, gaylussite) reflecting the progressive infilling and shallowing of the basin. The saltpan surface has been exploited historically for its sodic brines.

Regular changes in sediment texture and composition characterize the Saltpan sequence; ~5 m-scale units of clastic (coarse silt and sand) sediments rich in carbonate and/or evaporite minerals alternate with ~5 m-scale units of finer, clay-rich terrigenous materials (Fig. 2). The carbonate component consists entirely of inorganic calcite and sodium carbonates (trona and gaylussite); the occurrence of these minerals reflects intervals when evaporation greatly exceeded precipitation and crater wall runoff supply. There is, however, no sedimentological evidence of complete drying of the lake in the form of desiccation cracks, palaeosols or unconformities; periods of low precipitation are, however, marked by poor or absent pollen records (Partridge *et al.*, 1993). In contrast, the fine-grained (high <20 μm percentage), carbonate-poor units appear to reflect wetter intervals when deep-water conditions prevailed. This inverse covariation between sediment texture (silt and clay percentages) and chemical composition (total carbonate percentage) was combined into a single variable using principal components analysis. The first eigenvector (PCI) of the analysis accounted for 61% of the total sediment texture and composition variance; PCI is shown adjacent to the raw lithologic data in Fig. 2.

In order to link the data from the lake sequence to past rainfall, sixteen pristine A-horizon soil profiles in eastern South Africa were sampled across a 440–1500 mm/year precipitation gradient to examine the relationship between soil sediment texture (expressed as the <20 μm percentage) and mean annual precipitation (MAP; mm/year). At each of these localities (Fig. 1) soils had developed from granitic bedrock. Weathering of the bedrock seemed to provide a quantifiable link between available moisture and the properties of the sediments which were introduced into the lake from the crater sides: studies across the east–west climatic gradient which exists over southern Africa have shown that, in accordance with predictions, the −20 μm fraction (silt + clay) of granite soil profiles varies primarily as a function of climate (e.g. Brink, 1979). Of importance is the fact that this relationship is independent of lithological variations. Although the textures of the granitic rocks of southern Africa vary considerably, this is reflected overwhelmingly in local variations in the *sand* fraction of the overlying soils, which is made up predominantly of quartz grains; the size distribution of these grains differs from one granite to another, and this is manifested in the size composition of the coarse fraction of the soils because quartz is largely unsusceptible to chemical breakdown under normal conditions of pH. In contrast, the silt and clay fractions (<20 μm), which are preponderantly the product of chemical decomposition of feldspars, micas and ferromagnesian minerals, are a function of soil moisture availability rather than rock texture. The resulting correlation coefficient between the <20 μm percentage and MAP gradient was high (*r*=0.88; Fig. 3), indicating that precipitation has been a strong determinant of pedogenesis in soils derived from granites. Soils formed under high rainfall conditions were consistently finer grained, whereas those developed under drier conditions were consistently coarser.

The Pretoria Saltpan lithologic data (Fig. 2) and the soil

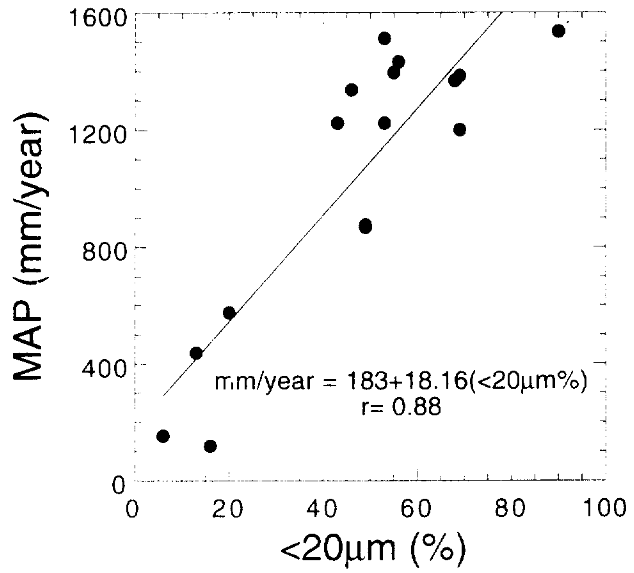

FIG. 3. Relationship between South African soil texture and regional precipitation. Sixteen pristine soil profiles developed on granitic bedrock were sampled across eastern South Africa (Fig. 1). The high correlation (*r*=0.88) between soil texture (represented as the <20 μm percentage) and the regional rainfall gradient reflects the strong influence of enhanced mean annual precipitation (MAP) on the granitic weathering and pedogenesis.

texture–precipitation regression (Fig. 3) were combined to produce a continuous late Pleistocene proxy record of South African rainfall variations. The first eigenvector of the principal component analysis (PC1) was first rescaled back to the original <20 μm fraction units by standard regression analysis, and the regression equation defining the correlation shown in Fig. 3 (rainfall (mm/year) =183+18.6 (<20 μm percentage)) was applied to yield a continuous palaeo-rainfall series. A simple hydrologic model (Schulze, 1989) was used to simulate the effects of reduced summer insolation, and hence lesser evapotranspiration, on this relationship; the results indicated a net reduction of ~5% in the estimated precipitation associated with particular 20 μm percentages during intervals of lowest insolation receipts. Although its overall effect is small, this reduction was used to modify the rainfall series so as to increase the accuracy of the proxy. The lacustrine sequence also contains some mass-flow deposits which decrease in frequency upsection (for a detailed record see Partridge *et al.*, 1993); these intervals were identified and stratigraphically removed to define a corrected depth scale for the final rainfall series. The corrected depth for the base of the lacustrine sequence was 72.7 m whereas the original drilling depth was 90 m. There is no evidence that significant erosion of the underlying sediments took place during these mass-flow episodes.

Conventional radiocarbon analyses of the extracted organic carbon fraction constrain the uppermost 43,000 years of the sequence (Table 1). This organic material consists of algal debris which was carefully separated from the mineral carbonates; the dates are considered reliable as downward translocation of organic fragments is highly unlikely in these fine lake deposits. The organic carbon ages were converted to calendar ages using the tree-ring and U/Th calibrations (Stuiver and Pearson, 1993; Bard *et al.*, 1993) with appropriate adjustments for the southern hemisphere (Vogel *et al.*, 1993). A mean lake reservoir correction of 1150-years was also applied, based on the aqueous isotopic chemistry of the Saltpan. This correction was necessary because of the presence of 'old' ^{14}C in the groundwater feeding the lake, which results in an apparent age of 1150 BP for contemporary lake water. The corrected, calibrated ages suggest an average sedimentation rate (using the corrected depth scale) of 37 cm/ka (Fig. 4). Extrapolation of this mean accumulation rate to the base of the lacustrine sediments suggests an age of ~195 ka for the onset of lacustrine deposition,

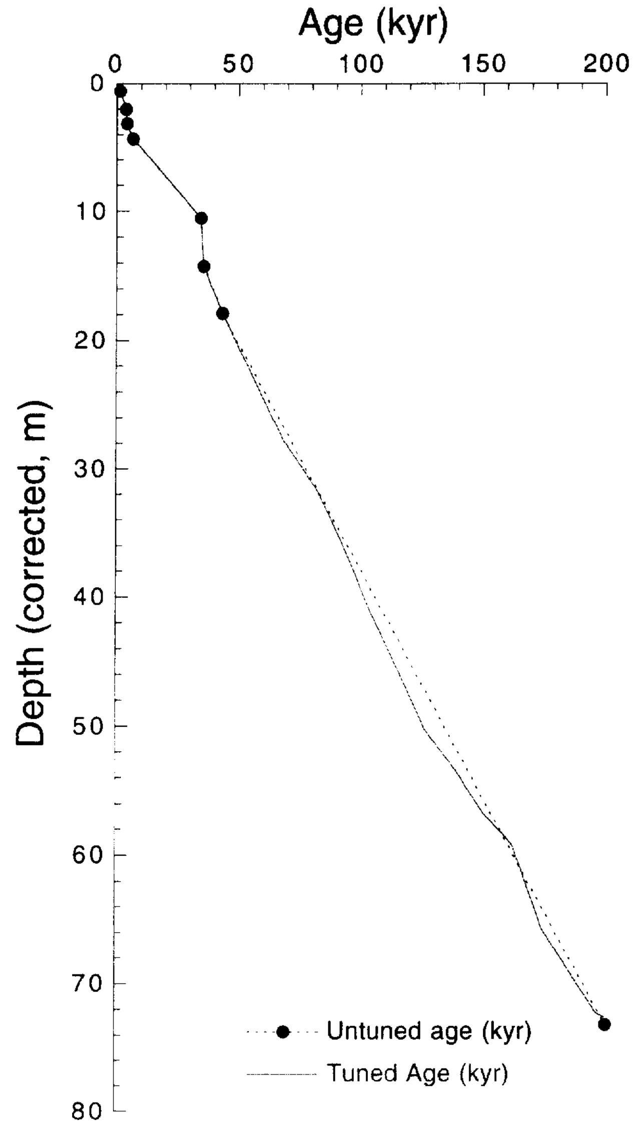

FIG. 4. Age-depth relation for the Pretoria Saltpan for the raw, untuned (dashed line) and the tuned (solid line) age models. Radiocarbon analyses of the extracted organic carbon fraction constrain the uppermost 43,000 years of the sequence. Mean sedimentation rates of ~37 cm/ka were derived from the calibrated, reservoir-corrected radiocarbon dates (shown). The onset of lacustrine deposition is estimated at 200,000 years based on fission-track analysis of the basal impact glasses of the saltpan crater. Extrapolation of the radiocarbon sedimentation rates to the base of the lacustrine sediments (72.7 m, corrected depth) suggest a basal age of 195,000 years. The age model derived by phase-locking (tuning) the estimated Pretoria rainfall record to the orbital insolation target (30°S, January) does not significantly deviate from this basic age model. The RMS mean deviation between the untuned (dashed line) and tuned (solid line) was 3.5±2.2 ka between 43–200 ka.

TABLE 1. Data for ^{14}C samples (organic matter)

Depth (cm)	Analysis no. Pta-	δ^{13}c(%)	^{14}C (pmC)	Age (radiocarbon yr BP)	Calibrated age (yr BP) with 1150 yr reservoir correction
237–245	5240	−17.3	75.90±0.57	2330±50	1180
382–388	5228	−16.8	58.68±0.39	4420±50	3730
492–500	5222	−17.0	57.32±0.45	4600±60	4140
612–618	5770	−20.2	41.19±0.40	7200±80	6780
1233–40	5225	−18.2	2.13±0.19	31,000±700	34,350
1600–10	5559	−13.7	1.79±0.17	32,500±750	35,650
1966–74	5180	−19.0	0.71±0.14	39,900±1600	43,350

which is in reasonable agreement with the ~200 ka fission-track estimate. Radiocarbon analyses of the mineral carbonate phases yielded highly variable, inconsistent and ultimately unreliable ages. Analysis of specific carbonate mineral phases indicated that secondary carbonate mineral precipitation and/or isotopic exchange between primary carbonate and pore waters may have affected the radiocarbon composition of these minerals (Partridge *et al.*, 1993).

SUBTROPICAL SOUTH AFRICAN CLIMATE: HIGH-LATITUDE ICE SHEET AND LOW-LATITUDE INSOLATION INFLUENCES

The Pretoria rainfall time series was constrained initially using the calibrated radiocarbon dates and the 200 ka age for the onset of lacustrine deposition. The resulting rainfall series (Fig. 5a) is characterized by well-defined, periodic (23,000-year) variations. Power spectral

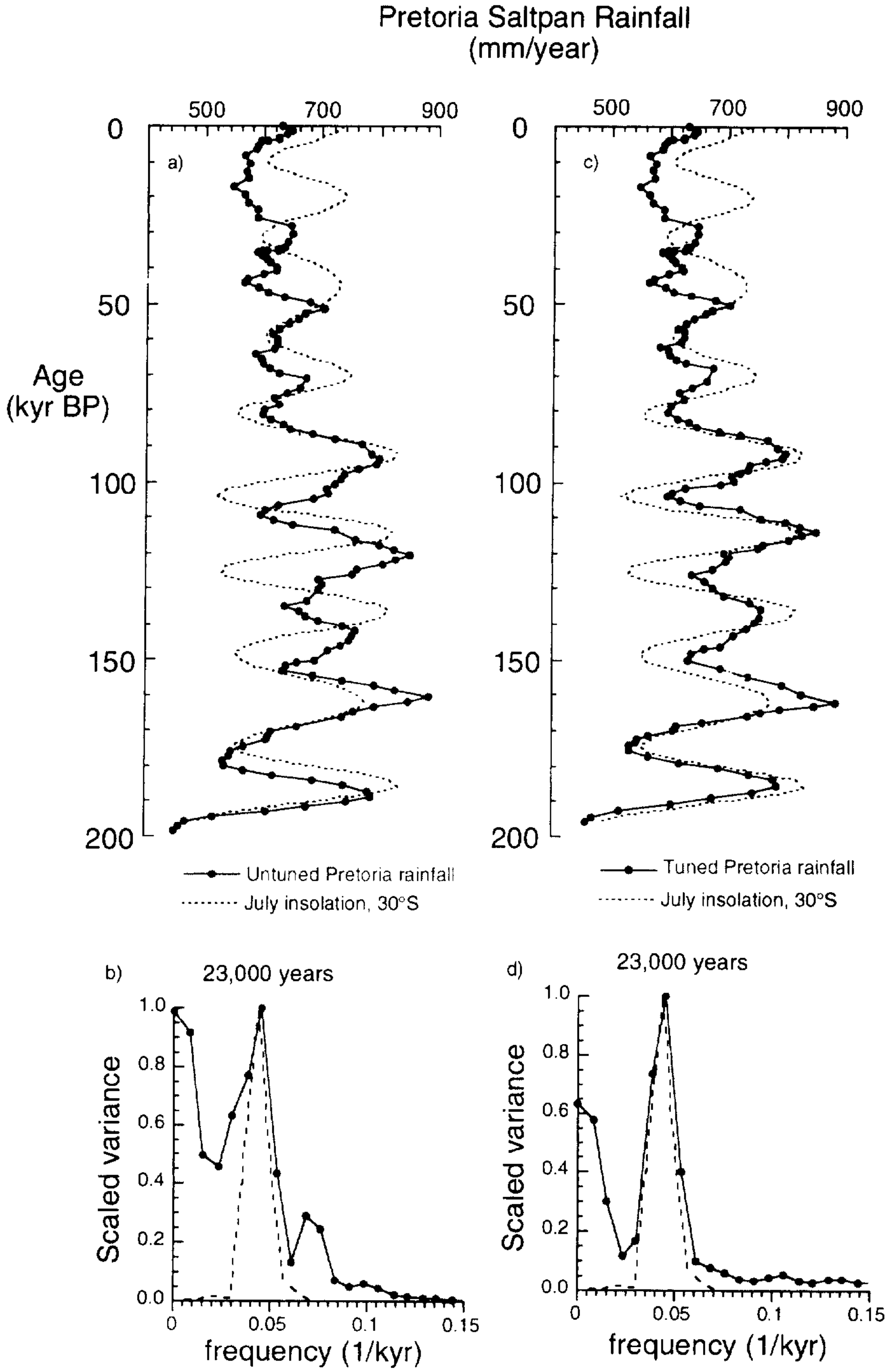

FIG. 5. The Pretoria Saltpan rainfall time series derived from the soil sediment texture and precipitation relation (Fig. 3) and the Pretoria Saltpan textural and compositional data (Fig. 2). Two age models were developed using (a) the raw corrected, calibrated radiocarbon ages and the 200,000-year age estimate for the base of the lacustrine sediments, and (b) using the orbitally-tuned (30°S, January) age model. Note the dominance of precessional (23,000-year) variability in the power spectrum of both the untuned and tuned rainfall time series, which accounts for 44% (untuned) and 46% (tuned) of the total variability.

analysis of this raw, untuned rainfall series (Blackman and Turkey, 1958) (Fig. 5b) indicates that this precessional variability accounts for 44% of the total rainfall variance over the 200,000-year duration of the record. This preliminary rainfall series is similar in amplitude and phasing to the calculated summer (January) insolation at 30°S (Fig. 5a; Berger, 1978), the latitude of maximum interior South African temperature seasonality and related climate response. The absence of absolute age control between 43–200 ka precluded the precise determination of phasing relationships between these forcing and response signals.

The reduced rainfall estimates for the last glacial maximum (~21 ka BP) agree with other South African terrestrial palaeoclimate evidence for regionally cooler (by 4–5°C) and drier (up to 50%) glacial conditions (Heaton *et al.*, 1986; Partridge, 1990; Talma and Vogel, 1992). Relatively dry conditions are also indicated for isotopic Stage 6 (150–130 ka BP), again consistent with available palaeoclimate data from the region (Partridge, 1990). The simultaneous development of cooler and drier glacial conditions in North Africa (Pokras and Mix, 1987; Gasse *et al.*, 1989; Street-Perrot and Perrott, 1990; Lezine, 1991; deMenocal *et al.*, 1993; deMenocal, 1995) and South Africa has been attributed to the coeval expansion of northern and southern hemisphere polar ice sheets (Denton and Hughes, 1981; Nelson *et al.*, 1985; Broecker and Denton, 1989) and their influences on subtropical African climate (deMenocal *et al.*, 1993; deMenocal, 1995).

Dominance of precessional variability in this untuned time series and its apparent close covariance with the calculated summer (January) insolation at 30°S (Berger, 1978; Fig. 5a) suggested that the timescale could be further constrained by phase-locking (tuning) the rainfall time series to the 30°S orbital insolation record. The raw rainfall time series was correlated to the summer 30°S insolation record between 43–200 ka using a series of tiepoints and stepwise linear age interpolations linking the correlative features. The dominant period of variation in the tuned Pretoria rainfall time series (23,000 years) and its relative proportion of total variance (46%) were essentially unchanged after the tuning process (Fig. 5c, d), nor did

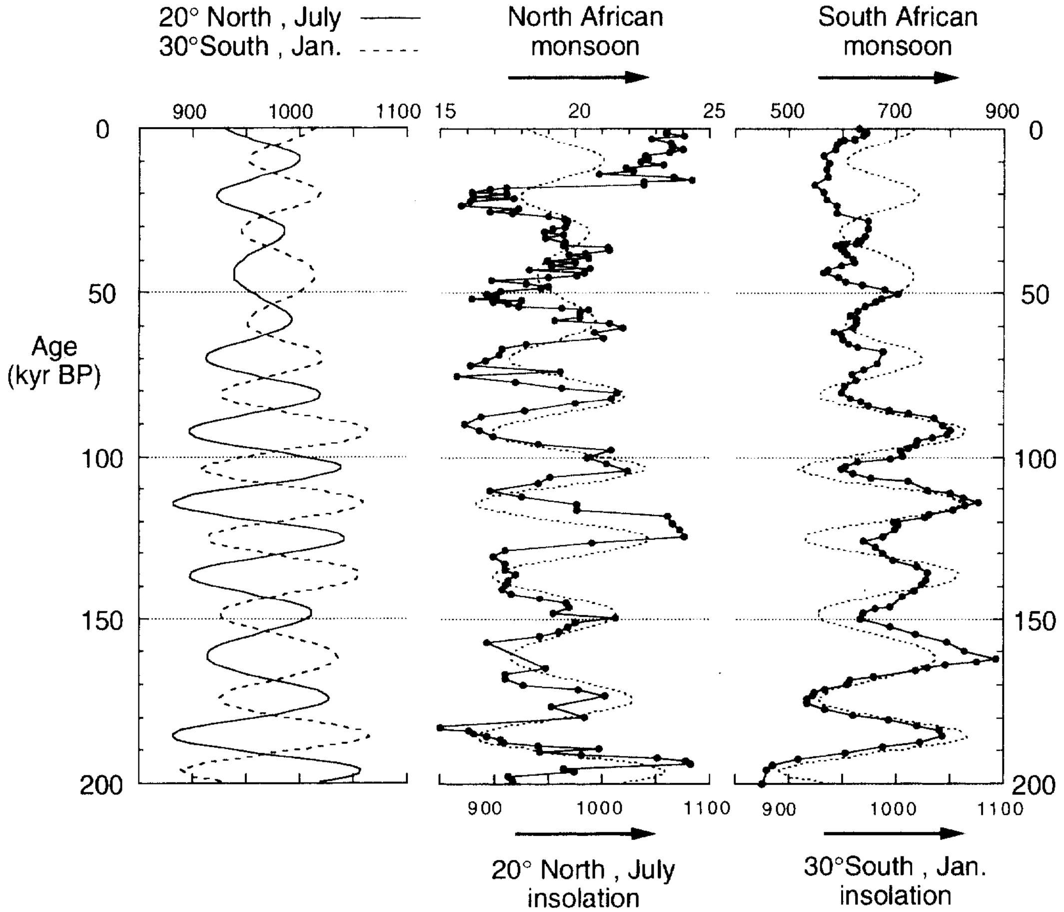

FIG. 6. The antiphase response of North and South African rainfall to orbital precession forcing of summer insolation. Late Pleistocene variations in the North African monsoon were reconstructed based on fossil faunal assemblage variations in deep-sea sediment core RC24-07 (McIntyre *et al.*, 1989). These data demonstrate that the North African monsoon was strengthened during times of maximum northern hemisphere summer season insolation (McIntyre *et al.*, 1989; e.g. 20°N, July), in accord with other palaeoclimate data (Street and Grove, 1979; Rossignol-Strick, 1983; Prell and Kutzbach, 1987; Pokras and Mix, 1987; Vogel *et al.*, 1993) and climate model simulations (Kutzbach, 1981; Prell and Kutzbach, 1987). The Pretoria Saltpan rainfall exhibits dominant precessional variability (Fig. 5a–d) consistent with the calculated changes in southern hemisphere summer insolation (e.g. 30°S, January; Fig. 5a–d). Comparison of these North and South African palaeoclimate records reveals the predicted antiphase response of North and South African subtropical climate to orbital precession changes in summer season insolation (Berger, 1978).

this significantly alter the age-depth profile defined by the radiocarbon and fission-track dates (Fig. 4). The tuning process adjusted the ages between 43–200 ka by an average absolute value of 3300±2300 years; the maximum single age adjustment was 8800 years. The close agreement between the tuned timed series and that obtained by interpolating the sedimentation rate between the oldest ^{14}C date and the mean basal fission track age (which is also very similar to the mean sedimentation rate over the period of the ^{14}C record) lends confidence to the inferred linkage between sedimentary cycles and precessional insolation variations.

PRECESSIONAL INSOLATION FORCING OF NORTH AND SOUTH AFRICAN SUBTROPICAL CLIMATE

The reconstructed late Pleistocene variations in South African rainfall agree well with the calculated sensitivity of subtropical precipitation to late Pleistocene variations in orbital insolation forcing derived from climate model experiments. Prell and Kutzbach (1987) defined a response-forcing sensitivity coefficient to quantify the northern subtropical monsoon rainfall response to direct insolation forcing for a series of climate model experiments with differing insolation boundary conditions. For the North African and South Asian monsoons, the estimated precipitation sensitivity coefficients were 5 and 2.5, respectively (i.e. 10% increases in summer insolation produced 50% and 25% increases in summer North African and South Asian rainfall, respectively; Prell and Kutzbach, 1987). The mean coefficient value for the entire northern subtropics (0–30°N) was 3.5. Our estimate for the southern subtropics from the Pretoria Saltpan rainfall data suggests a sensitivity coefficient value of 4.5; the rainfall record varies between 535–900 mm/year (68%) relative to a range of 920–1060 W/m^2 (15%) in summer insolation.

Earth orbital precession affects the seasonal distribution of solar insolation such that resulting changes in summer season insolation are antiphase between hemispheres. Precessional increases in summer (JJA) insolation in the northern subtropics are balanced by decreases in summer (DJF) insolation in the southern subtropics. This antiphase relationship between North and South African palaeoclimate records has yet to be convincingly demonstrated. The Pretoria Saltpan record is the one of the few long and continuous palaeoclimate records from the southern hemisphere subtropics; as such, it provides a fundamental test of the role of orbital forcing on global subtropical climate.

Both the North and South African palaeo-rainfall records are dominated by precessional variance (Fig. 5) and are in-phase with their respective hemispheric summer seasonal insolation records (Fig. 6). However, the northern and southern hemisphere palaeoclimate records themselves, like the insolation records, are antiphase. Tropical Atlantic sea-surface temperatures are linked to the North African monsoon due to monsoonal wind-driven upwelling of cold, nutrient-rich subsurface waters (Philander and Pacanowski, 1986; Servain and Legler, 1986). When North African summer monsoon winds were strengthened by precessional increases in northern summer (JJA) season insolation, upwelling was reduced and warmer SSTs prevailed in the eastern tropical Atlantic (McIntyre *et al.*, 1989; Molfino and McIntyre, 1990). These data demonstrate that both subtropical North and South African climate were strongly responsive to changes in summer season insolation resulting from earth orbital precession, and that the climatic responses were out-of-phase between hemispheres.

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