A late Pleistocene–Holocene multi-proxy record of palaeoenvironmental change from Still Bay, southern Cape Coast, South Africa

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ABSTRACT: The southern Cape is a key focus for southern African palaeoenvironmental research as it represents the transitional region between temperate westerlies and sub-tropical rainfall sources. This study presents pollen, plant biomarker, geochemical and charcoal data preserved in the Rietvlei wetland. The bulk of the record spans the last 16 ka, but it also provides rare insights into late Marine Oxygen Isotope Stage (MIS) 3 (ca. 35–30 k cal a BP). The data suggest that during the Pleistocene the development and permanence of this wetland was probably influenced by sea-level change via control on the local water table; notably lower sea levels within MIS 2 resulted in very limited wetland productivity. The MIS 3 section provides evidence both supporting previous suggestions of relatively humid conditions, but also some indication of periodic arid phases. The Holocene record suggests clear contrasts between the early (11–7 k cal a BP; relatively humid), mid-Holocene (7–3.3 k cal a BP; more arid, less productive wetland conditions) and latest Holocene (last 2 k cal a BP; resurgence in both fynbos and aquatic/riparian pollen). While isolating the roles of winter/summer rainfall remains challenging, these data clarify the nature of change during key episodes in the regional palaeoenvironmental record.

KEYWORDS: Holocene; late Pleistocene; multi-proxy record; southern Cape palaeoenvironments; South Africa.

Introduction

The southern Cape coast of South Africa currently encompasses the transition between (i) the southern African winter rainfall zone in the west, which receives most of its precipitation from seasonal migrations of the southern westerlies, and (ii) the summer rainfall zone in the east, where moisture is primarily advected from the Indian Ocean during the summer (Chase and Meadows, 2007; Fig. 1). As a result, it receives precipitation from multiple potential sources, and much of the region presently experiences a largely aseasonal rainfall regime. However, as the influence of both winter and summer moisture-bearing systems was highly variable during the late Quaternary (Talma and Vogel, 1992; Parkington et al., 2000; Truc et al., 2013; Chase et al., 2015), the southern Cape has been identified as being a particularly sensitive climatic region, with potentially radical changes in rainfall seasonality and amount (Chase and Meadows, 2007). Such sensitivity (and complexity) is also compounded by the nature of change during key episodes in the regional palaeoenvironmental record. Despite their botanical significance and high conservation status, there is almost no palaeoenvironmental/ecological data pertaining to the history of these coastal lowlands. Most published data comprise fragmentary records (e.g. Martin, 1968; Schultz, 1986; Carr et al., 2006), often not extending beyond the Holocene, and a coherent history of long-term environmental/ecological change remains to be established.

Here we report the palaeoenvironmental records preserved in the Rietvlei wetland near Still Bay on the Riversdale Plain (Fig. 2). Through analysis of sediments from a core extracted at this site, we investigate the relationship between changing rainfall seasonality and vegetation dynamics, including the responses of particular vegetation types (fynbos and non-fynbos communities) to late Quaternary environmental change.

An initial study of the Rietvlei–Still Bay site (Carr et al., 2010) demonstrated the preservation of a record encompassing the last 37 ka. That study focused on the site's organic geochemical record (using pyrolysis-gas chromatography/ mass spectrometry; py-GC/MS), and changing organic matter (OM) preservation and provenance. The present study (based on the same core as the initial study by Carr et al., 2010) seeks to build on this through the development of a more detailed site chronology and new lines of proxy evidence, including pollen and microscopic charcoal, as well as an expanded stable isotope and plant leaf wax lipid dataset. The specific objectives are to characterize the local wetland conditions at Rietvlei–Still Bay and to reveal palaeovegetation and associated palaeoclimatological evidence that offers new
insights into the nature of climate and ecological change along the southern Cape coast during the late Pleistocene and Holocene.

Study Region and Site Description

Location, geology, geomorphology and climate

The sediment core analysed for this study was extracted from Rietvlei (34°21.249'S; 21°32.127'E, 17 m a.s.l.), an elongated wetland (approximately 3.5 km long and 100 m wide) situated on the Riversdale Plain about 8 km east of the town of Still Bay and ~300 km east of Cape Town (Fig. 2). The wetland occupies a distinct topographic depression between two shore-parallel coastal barrier dunes and probably originated as an inter-dunal slack lake (Roberts et al., 2008). The landwards barrier comprises well-cemented aeolianite of the Waenhuiskrans Formation, which was probably established within Marine Oxygen Isotope Stage (MIS) 7 whereas the seawards barrier was formed during and subsequent to the last Inter-glacial sea-level highstand (MIS 5e; ~125 ka) (Roberts et al., 2008). The area is underlain by Bokkeveld Group mudrocks (part of the Cape Supergroup). Up to 8 m of sediment has accumulated within Rietvlei, a substantial proportion of which comprises alluvial (calcareous) silty sands. The upper 3 m of sediment contains significant amounts of OM. Today the waters of the wetland are moderately alkaline and are covered with a floating mat of vegetation, dominated by Phragmites australis.

Precipitation at the site averages ~400 mm (Climate Systems Analysis Group, 2012) and the climate is classified as semi-arid. Situated in the year-round rainfall zone (YRZ; sensu Chase and Meadows, 2007; Fig. 1), precipitation is distributed in a relatively uniform pattern throughout the year. During the winter months, the expansion of the circumpolar vortex drives the equatorward migration of the westerly storm track, while in the summer months, higher sea-surface temperatures and increased easterly flow result in precipitation events. It has been suggested that as a function of changes in global glacial–interglacial boundary conditions, reductions, or even cessations, in the contributions of these moisture-bearing systems may have occurred, resulting in shifts between a year-round, summer or winter rainfall climate (Chase and Meadows, 2007). This may have meant the potential development of a pronounced drought season, which currently exists to the west in the purely winter-rainfall Western Cape.

Contemporary vegetation

The aeolianite ridge north of Rietvlei is dominated by endemic-rich limestone fynbos (Mustart et al., 2003; Fig. 2). The distribution of limestone fynbos is largely controlled by edaphic factors and it is only found on the alkaline soils of the Bredasdorp Group limestones and aeolianites. Due to its highly specialized and restricted nature, it represents one of the most threatened fynbos vegetation types (Cowling and Holmes, 1992; Willis et al., 1996). Structurally, limestone fynbos is dominated by asteraceous, restioid and proteoid fynbos with graminoid and ericaceous fynbos largely absent (Mucina and Rutherford, 2006). Sand fynbos borders the patches of limestone fynbos (Fig. 2), and is more extensive than the limestone fynbos, being concentrated within valleys and on the coastal plain. It is structurally defined as proteoid fynbos and characterized by medium to tall open shrublands (Mucina and Rutherford, 2006). To the south of the site, the

Fig. 1. The location of the southern Cape (black box) in relation to generalized atmospheric and oceanic circulation patterns. ABF, Angola–Benguela Front; CAB, Congo Air Boundary; ITCZ, Inter Tropical Convergence Zone.
coastal dune crests and their landward slopes are vegetated by coastal thicket (‘strandveld’), comprising a high cover of tall non-proteoid trees and shrubs (e.g. *Sideroxylon inerme* and various trees of the family Celastraceae) and a high presence of fleshy-leaved shrubs (e.g. *Zygophyllum morgana*) (Rebelo *et al*., 1991; Mustart *et al*., 2003). This vegetation type is characterized by the co-dominance of *Euclea racemosa* and *Olea exasperata*. The thicket elements form a mosaic with dune asteraceous fynbos on the neutral sands to the south-west and south-east of the site (Rebelo *et al*., 1991; Mucina and Rutherford, 2006; Fig. 2). The wetland itself is extensively covered by *Phragmites australis*. Also within the floating mat of emergent vegetation are various Juncaceae, Cyperaceae, Apiaceae and Araceae species, as well as true aquatic elements such as *Aponogeton* sp.

**Materials and Methods**

**Core extraction**

An undisturbed continuous sediment sequence was extracted with a portable vibracorer (adapted from Lanesky *et al*., 1979; detailed methodology found in Baxter, 1996). Two field excursions to Rietvlei in 2007 and 2009 yielded three cores. All three cores revealed comparable stratigraphies; Rietvlei–Still Bay 2 (RVSB-2) was assessed as having the greatest potential for the generation of a multi-proxy palaeoenvironmental record and is therefore the focus of this study. After retrieval, RVSB-2 was split in the laboratory, initially under darkroom conditions, to allow sampling for optically stimulated luminescence (OSL) dating. Following this, sequential sub-sampling took place along the length of the core for radiocarbon, pollen and charcoal (combined within one sample), sedimentological and various geochemical analyses.

**Chronology**

The RVSB-2 age model was constructed from a combination of radiocarbon and OSL ages (Table 1). Initially, four radiocarbon ages were obtained from the Department of Geosciences, University of Arizona using gas proportional counting. Samples were pre-treated with hydrochloric acid (HCl) and sodium hydroxide (NaOH) (to remove any alkali-soluble organic carbon) and rinsed with dilute HCl. Samples were combusted in oxygen to produce CO₂ and purified. Four accelerator mass spectrometry (AMS) radiocarbon samples were subsequently taken from positions in the core related to significant changes in OM composition and provenance (see Carr *et al*., 2010). The AMS samples were processed at the CHRONO Centre, Queen’s University Belfast. These samples were treated with HCl (4%), and heated to 80°C for 2–3 h. This was followed by NaOH
Table 1. Uncalibrated ages and calibration details for RVSB-2.

| Lab code   | Average depth (cm) | Measurement method | $^{14}$C age (a BP) | $F^{14}$C ($\pm 1\sigma$) | 1 sigma error | Calibration data | 95.4 % (2$\sigma$) cal BP age range | Relative area under distribution | Median probability | Date (2$\sigma$) range (AD) | OSL age (ka) | OSL age error (ka) |
|------------|-------------------|-------------------|-------------------|--------------------------|---------------|-----------------|-------------------------------|-------------------|------------------|----------------|------------------|
| UBA-19735  | 2.5               | AMS               | Greater than modern$^{*}$ | 1.0103 ± 0.0048          | Southern Hemisphere Zones 1 and 2$^{†}$ | 95.4 % (2$\sigma$) cal BP age range | 1955–1957 |                             |                             |                 |                 |
| A-14919    | 88.0              | GPC               | 1260              | 70                        | SHCal13$^{‡}$ | 977–1274         | 1                             | 1133              |                 | 6103           |                 |
| A-15438    | 133.0             | GPC               | 5365              | 60                        | SHCal13$^{‡}$ | 5942–5973        | 0.870                         | 5984–6221         |                 | 6232–6275      | 0.000           |
| A-14938    | 207.5             | AMS               | 8166              | 39                        | SHCal13$^{‡}$ | 8990–9144        | 0.900                         | 9067              |                  | 11.27          | 0.6             |
| Shld08157  | 224.5             | OSL               | 10250             | 120                       | SHCal13$^{‡}$ | 11 397–12 319    | 0.946                         | 11 881            | 12 321–12 404   | 0.054          |                 |
| A-15438    | 274.5             | AMS               | 13 439            | 58                        | SHCal13$^{‡}$ | 15 837–16 246    | 1                             | 16 050            |                  |                 |                 |
| UBA-19737  | 331.5             | AMS               | 29 496            | 264                       | SHCal13$^{‡}$ | 33 024–34 094    | 1                             | 34 189            |                  |                 |                 |
| A-14937    | 351.5             | GPC               | 27 630            | 1065                      | SHCal13$^{‡}$ | 29 546–33 842    | 1                             | 32 280            |                  |                 |                 |

$^{*}$Modern = 1950 AD.
$^{†}$Hua et al. (2013).
$^{‡}$Hogg et al. (2013).
AMS, accelerator mass spectrometry; GPC, gas proportional counting; OSL, optically stimulated luminescence; $F^{14}$C, fraction modern.
each section through multiple Markov Chain Monte Carlo (MCMC) iterations. 

The radiocarbon ages were calculated using the Libby half-life of 5568 years following Suiver and Polach (1977). The ages were corrected for isotope fractionation using the AMS-measured Δ13C, which accounts for both natural and machine fractionation. The radiocarbon chronology was augmented with an OSL sample (Shfd08157) from 224.5 cm. The OSL age was obtained on extracted and cleaned coarse grained (180–250 μm) quartz with a palaeodose ($D_p$) measured using the single aliquot regeneration protocol (further details are provided in Bateman and Catt (1996) and Roberts et al. (2008)). $D_p$ of 7.1 ± 0.09 Gy was obtained from 24 measured replicates which were normally distributed with a low over-dispersion (OD = 7%). Dose rates were derived from elemental concentrations obtained from inductively coupled mass spectrometry suitably attenuated for sediment size and moisture content. The latter were based on the contemporary (measured) content of the sub-sample with an uncertainty of 5% to account for potential changes in wetland conditions. As the sand-rich layer sampled for OSL was thin, dose rates were measured for adjacent units and the gamma contribution from these units was factored in to the final dose rate using gamma gradients as reported by Aitken (1985). The cosmic dose contribution was derived from the equation of Prescott and Hutton (1994). The final calculated dose rate for sample Shfd08157 was 0.63 ± 0.027 Gy ka⁻¹.

The software package Bacon (version 2.2) (Blaauw and Christen, 2011) was used to integrate the chronological information and to develop an age–depth model (Fig. 3). Using a Bayesian statistics framework, this method divides the core into sections and models the accumulation rate for each section through multiple Markov Chain Monte Carlo iterations. ¹⁴C ages were calibrated with the SHCal13 curve (Hogg et al., 2013) and the post-bomb age was calibrated with the Southern Hemisphere post-bomb curve of Hua et al. (2013). The OSL age with its uncertainties was incorporated into the age–depth model as a ‘calibrated’ age.

**Bulk sample OM content**

Bulk geochemical analyses comprising total organic carbon (TOC), total nitrogen (TN) and Δ13C were carried out using a SerCon ANCA GSL elemental analyser interfaced to a SerCon Hydra 20–20 continuous flow isotope ratio mass spectrometer. For the determination of TOC and Δ13C samples were pre-treated with 10% HCl to exclude inorganic carbon. All analyses were carried out in triplicate with a typical precision of ~0.05% for elemental concentrations and 0.1% for Δ13C.

**Pollen analysis**

For pollen and microscopic charcoal analyses, the sub-sampling interval was guided by stratigraphic complexity. An initially coarse sampling resolution (~10 cm) was refined (~1–5 cm) to better characterize what were identified as periods of significant vegetation change. The extraction of palynomorphs followed standard methods for the removal, disintegration and dissolution of the non-pollen matrix (Moore et al., 1991) with specific adaptations for dense media separation from Nakagawa et al. (1998). This involved 30% HCl treatment to remove carbonates, 10% KOH digestion to disaggregate the samples and remove humic acids, heavy liquid mineral separation using ZnCl2 to separate the pollen grains from the mineral fraction (Faegri and Iversen, 1989; Moore et al., 1991; Nakagawa et al., 1998) and, for samples with high clay content, HF treatment to remove remaining siliceous material. Samples were acetolysed and mounted in Aquatex (aqueous mounting agent). Three slides were produced per sample. To determine absolute pollen concentrations, Lycopodium spores were added (Stockmarr, 1973) prior to physical and chemical processing to ensure even losses amongst fossil and exotic grains during processing.

Pollen counts of 500 grains per sample were carried out at 400× magnification for routine identification and 1000× for specific identification. Spores and other non-pollen palynomorphs were also counted, but not included in the total pollen sum. Pollen taxa were identified using the University of Cape Town’s reference collection and published literature (van Zinderen Bakker, 1953, 1956; van Zinderen Bakker and Coetzee, 1959; Welman and Kuhn, 1970; Scott, 1982). The pollen and microscopic charcoal diagrams were divided into statistically significant pollen assemblage zones based on a CONISS (Constrained Incremental Sum of Squares) (with square root transformation) analysis (Grimm, 1987).

**Microscopic charcoal analysis**

Charcoal particles were identified and counted on the same microscope slides produced for the pollen analysis. Only particles that were black, opaque and angular were considered charcoal fragments (Patterson et al., 1987; Mooney and Tinner, 2011). Charcoal fragments were classified and counted according to two size groups based on the long axis of each fragment; 10–100 and 100–150 μm. Particles less than 75 μm² (or ~10 μm long) were not counted due to the risk of false identification (Mooney and Tinner, 2011). Therefore, our charcoal signal primarily relates to the regional (10–100 μm) and local (100–150 μm) fire signals and...
excludes extra-regional fires (<10 µm). Absolute charcoal abundances were calculated in the same manner as pollen concentrations (Stockmarr, 1973).

Leaf wax lipids

In South Africa, recent studies have shown that the relative abundances of leaf wax n-alkanes may be an environmentally sensitive parameter (Carr et al., 2014; 2015). Additionally, the relative abundance of short and long chain length n-alkanes in lacustrine and wetland contexts has been associated with changes in the contribution of aquatic and riparian plant types to sedimentary OM (e.g. Ficken et al., 2000).

Here we present data for leaf wax n-alkane distributions for the Rietvlei sediments. Leaf wax lipids were extracted from 5–10 g of powdered sediment using a soxhlet extraction system [24 h: hexane/dichloromethane (DCM)/methanol, ratio 1:2:2]. The extracts were rotary evaporated and purified over a sodium sulphate column. The apolar fraction was isolated via Al₂O₃ column chromatography using a hexane/DCM/a sodium sulphate column. The extracts were rotary evaporated and purified over a sodium sulphate column. The apolar fraction was isolated via Al₂O₃ column chromatography using a hexane/DCM/a sodium sulphate column.

CPI was calculated following Bray and Evans (1961): CPI = \[\frac{1}{\sum_{i=4}^{34} \frac{C_i}{C_1}}\] (1)

where \(C_i\) is the concentration of the n-alkane with \(i\) carbon atoms.

The average chain length (ACL) was calculated as per eq. (2), which is equivalent to the weighted mean of all odd chain length n-alkanes, following Poynter et al., (1989):

\[ACL_{23–33} = \left( \frac{23 \times C_{23} + 25 \times C_{25} + 27 \times C_{27} + 29 \times C_{29} + 31 \times C_{31} + 33 \times C_{33}}{C_{23} + C_{25} + C_{27} + C_{29} + C_{31} + C_{33}} \right)\] (2)

where \(C_i\) is the concentration of the n-alkane with \(i\) carbon atoms.

A ratio of shorter to longer chain length n-alkanes (the \(P_{aq}\) index) has been used to differentiate aquatic and emergent vegetation inputs. Such an approach was initially based on measurements of modern emergent and aquatic plants in East African lakes. It is calculated following Ficken et al (2000):

\[P_{aq} = \left( \frac{C_{23} + C_{25}}{C_{23} + C_{25} + C_{29} + C_{31}} \right)\] (3)

A higher \(P_{aq}\) is associated with a greater proportion of shorter chain length n-alkanes and therefore larger contributions of emergent or aquatic vegetation relative to terrestrial vegetation.

Pyrolysis gas chromatography mass spectrometry

py-GC/MS analyses can be used to characterize complex (insoluble) macromolecular OM (Nierop, 1998; Kaal et al., 2007). The technique thermally fragments this macromolecular material into GC-amenable products and the resulting pyrolys products are interpreted in terms of their probable precursor macromolecules (e.g. lignin monomers and cellulose) which are potentially diagnostic of OM provenance and/or preservation (e.g. Vancampenhout et al., 2008; Carr et al., 2013). Carr et al. (2010) presented a suite of py-GC/MS data for 22 samples from the RVSB2 core. These demonstrated marked downcore changes in OM composition, and were inferred to reflect the combined effects of changing OM preservation and changes in OM provenance (particularly the presence of algal lipids). Here, these effects were inferred using axes 1 and 2 from a de-trended correspondence analysis (DCA, conducted in Past (Hammer et al., 2001)) of the complete py-GC/MS dataset from Rietvlei. Here we include the axis 1 (OM preservation) and 2 (OM source) scores, now integrated with the site’s improved age-depth model as an additional proxy data source. Methodological information and further details are provided in Carr et al. (2010).

Results

Stratigraphy and chronology

The 360-cm core consists primarily of poorly sorted silty sands with slightly higher clay and silt fractions at 130 cm and from 280 to 325 cm (Fig. 3). The 380–325 cm section is distinct from the rest of the sequence, comprising pale carbonate-rich marls with leint orange mottles. The top 70 cm of the core contains abundant macro-plant remains predominantly of Phragmites australis. Mollusc shells and fragments of other marine micro-fauna were found throughout most of the core and are especially prevalent between 150 and 280 cm. These are most likely derived from the aeolianite and active coastal dunes that flank the site.

The bulk of the RVSB-2 record spans the last 16 k cal a BP (Table 1; Fig. 4) including the terminal glacial period (~16–11.7k cal a BP) and the Holocene (11.7k cal a BP to present). Orange mottles evident between 280 cm (~16k cal a BP) and 325 cm represent minor oxidation that could be a result of shallow-water conditions in the wetland or subaerial exposure of the sediment during that period (Carr et al., 2010). It is not possible to establish a reliable chronology for this unit. At 325 cm, an abrupt contact between the grey, carbonate clays and the underlying organic-rich sediments indicates a likely hiatus in the sequence. The two radiocarbon ages from the basal peat, while inverted and measured with different techniques, are within errors of one another. We do not apply an age–depth model to this unit, but consider the proxy data as a snapshot of environmental conditions ~30–35k cal a BP.
Pollen and microscopic charcoal analyses

A total of 86 samples were processed for pollen and microscopic charcoal analysis. Pollen preservation was variable, with relatively high pollen concentrations (mean $\approx 7.2 \times 10^4$ grains g$^{-1}$) within the top 2 m of the core, below which concentrations dropped considerably towards the base. Two sections of the core, from 220 to 260 cm and 290 to 325 cm (corresponding to the base of a sand layer and the calcareous/clay-rich zone; Fig. 3), were either devoid of pollen or contained excessively low concentrations.

Five pollen zones were identified (on the basis of the CONISS analysis). The most distinctive features of the lowermost pollen assemblage zone (RVSB-2-A; $\approx$35–30k cal a BP, the basal unit) is the high microscopic charcoal amounts and concentrations and high percentages of Geraniaceae pollen (Figs 5 and 6). There are relatively elevated proportions of Aizoaceae, Crassulaceae, Ruschia-type, Euphorbia, Artemisia and Anthospermum-type pollen in comparison with the rest of the sequence. Local wetland taxa percentages, notably Cyperaceae and Juncaceae, are low. Above the marls (representing ca. 30–16k cal a BP, and lacking preserved pollen), pollen zone RVSB-2-B ($\approx$16–11k cal a BP) is characterized by an abundance of Asteraceae, Stoebe-type and ChenoAm-type. The last-named reaches exceptionally high percentages (30–50%) between 13.8 and 12.3k cal a BP coinciding with increased charcoal concentrations and relatively low percentages of aquatic/riparian pollen.

The oldest section of zone RVSB-2-C (total age range $\approx$11–7k cal a BP) comprises only two levels with sufficient pollen for analysis at 11 and 9.7k cal a BP. These samples are characterized by extremely high percentages of Poaceae pollen. After 9.7k cal a BP, pollen concentrations increase significantly. Proteaceae percentages increase from 9.3k cal a BP until the top of RVSB-2-C, Stoebe-type proportions are elevated from 9.3 to 8.9k cal a BP and Asteraceae peaks from 9.3 to 8.5k cal a BP before tapering towards the top of the zone. A similar trend is evident for charcoal amounts and concentrations. Local aquatic and riparian taxa percentages, notably Cyperaceae and Aponogeton, are relatively high from 9.3k cal a BP to the top of RVSB-2-C. Cyperaceae generally increases towards the top of RVSB-2-C, reaching a maximum of nearly 40%, and from this point until the late Holocene remains the dominant pollen type.

The most distinguishing features of zone RVSB-2-D ($\approx$7.0–0.8k cal a BP) are prominent peaks in Passerina (27%) at 2.6k cal a BP and Proteaceae (29%) pollen at 2k cal a BP and the continued high percentages of Cyperaceae throughout the zone. Proteaceae percentages (together with many other fynbos elements) are relatively low for the lower half of the zone (from 7.0 to 2.6k cal a BP) increasing to 10–30% at the top (from 2.2 to 0.8k cal a BP).
BP). *Dodonaea* reaches its highest percentage at 2.7k cal a BP. Other coastal thicket taxa are slightly elevated (e.g. *Euclea*) in comparison with previous zones. Among the afrotropical elements, *Grewia* is absent for much of this pollen zone. There are discrete peaks in Aizoaceae and Crassulaceae at 3.9k cal a BP. Charcoal concentrations are high near the base and at the top of RVSB-2-D. Among the aquatic and riparian pollen types, RVSB-2-D shows a reduction in the abundance of Juncaceae, *Aponogeton* and Urticaceae. Total charcoal amounts generally increase towards the top of RVSB-2-D, although there are discrete peaks in both size classes near the base of the zone (at 6.5k cal a BP).

The uppermost pollen zone (RVSB-2-E; ~0.8–0k cal a BP) is primarily defined by the greater proportions of coastal thicket taxa (e.g. Celastraceae, *Dodonaea*, *Euclea* and *Olea*).
There is an increase in local wetland taxa with significant peaks in Aponogeton, Plantago, and Cyperaceae. Charcoal amounts and concentrations are generally low within zone RVSB-2-E, while pollen concentrations are extremely high (reaching $3.9 \times 10^7$ grains g$^{-1}$ at the base of RVSB-2-E).

**Bulk-sample geochemistry**

The bulk geochemical variables (TOC, TN, TOC/TN, Fig. 7) correlate well with pollen concentrations and indicate that the degree of pollen preservation is closely associated with the depositional environment. The py-GC/MS data (specifically DCA axis 1; Fig. 7) similarly demonstrate very varied OM preservation and this parameter closely tracks TOC (Carr et al., 2010), which varies down-core from 0.5 to 30%. In general, TOC is highest within the top 200 cm of the core ($\sim 8.5$k cal a BP), with particularly high values associated with pollen assemblage zone RVSB-2-D ($\sim 7–0.8$k cal a BP) (Fig. 7). The lowest TOC amounts are observed in zones RVSB-2-B, RVSB-2-C and the region of the core devoid of pollen ($\sim 30–16$k cal a BP). Short periods of low TOC are also seen at 5.0–4.1 and 0.7–0.4$k cal a BP. TN follows a similar trend to TOC and ranges between 0.02 and 2.06% (Fig. 7). The pyrolysis data indicate relatively poor preservation of OM at 16–30 and 6–1.5$k cal a BP (Fig. 7), with much higher productivity and/or preservation inferred from 14$k cal a BP, 9–6$k cal a BP (which includes the increased preservation of lignin-derived pyrolysis products, perhaps indicative of more anaerobic conditions than preceding and subsequent periods; Carr et al., 2010) and during the last 1.5$k cal a BP.

In general, $\delta^{13}C_{TOC}$ is fairly constant at ca. $-22$‰ [which is more enriched than the pure C_{1} vegetation; $\sim -27$‰ (O’Leary, 1981)] except for clear excursions to lower values ($\sim 25$ to $-28$‰) at 8.8–6.5$k cal a BP, at 2.1–1.2$k cal a BP and within zone RVSB-2-A (Fig. 7). The TOC/TN ratio is relatively constant for the upper 200 cm of the core, and fluctuates around an average of 16. The lower section is characterized by greater variability with values ranging from 6.7 to 58.2 (Fig. 7). TOC/TN values rise steadily from the top of zone RVSB-2-C to zone RVSB-2-A. Apart from four data points (246 cm/11.2$k cal a BP, 120$ cm (4.5$k cal a BP, 6$ cm/ 0.05$k cal a BP and 4$ cm/ 0.02$k cal a BP), all TOC/TN values are greater than 10, indicating that the OM within the core is largely derived from vascular plants (Meyers, 1994; Lamb et al., 2006).

**Leaf wax lipids**

The apolar lipid extracts are dominated by series of homologous n-alkanes spanning the chain length range C_{23}–C_{33}. Concentrations are generally low, and range between 2.2 and 0.1$ \mu g^{-1}$ (dry weight). n-Alkane concentrations are positively correlated with TOC. The n-alkane distributions display a characteristic odd over even chain length preference, which is typically indicative of a higher plant origin (Eglinton and Hamilton, 1967; Pancost and Booth, 2004). The average chain length (ACL_{23–33}) of the extracted n-alkanes ranges from 28 to 31 carbon atoms (Fig. 7), reflecting the dominance of the C_{29} and C_{31} n-alkanes in the majority of samples. This is consistent with a higher plant origin and is within the range of modern fynbos vegetation (Carr et al., 2014). ACL_{23–33} shows considerable down-core variability, although with the exception of the most recent sample (22$ cm) and the basal sample (360$ cm), the C_{31} is always the dominant n-alkane. The proportion of shorter chain length (C_{27–24} homologues is the major cause of this ACL_{23–31} variation. This variability is characterized by the $P_{aq}$ index (Ficken et al., 2000), which was proposed to be indicative of the contribution of non-emergent aquatic macrophytes relative to emergent aquatic and terrestrial plants. $P_{aq}$ is therefore commonly used to represent changes in aquatic plant inputs to OM within sedimentary sequences. Overall, the $P_{aq}$ index is low throughout the record and is indicative of dominantly terrestrial or riparian vegetation inputs throughout the sequence. This, however, consistent with the TOC/TN data and the py-GC/MS data. The highest $P_{aq}$ (and shortest ACL_{23–33}) values are seen at ca. 14$k cal a BP, 11–8$k cal a BP (RVSB-2-C) and during the last 1$k cal a BP (RVSB-2-E). Relatively low values are observed throughout RVSB-2-D, where the C_{29} and C_{31} n-alkanes are the dominant leaf waxes. The ratio of these two homologues is largely constant throughout the Lateglacial and the majority of the Holocene, with the exception of the last 1000 years. The ratio C_{31}/(C_{29}+C_{27}) averages 0.67 ± 0.04 from 16 to 1$k cal a BP (i.e. pollen zones RVSB-2-B to RVSB-2-D).

**Discussion**

**Depositional environment**

The most marked feature of the sedimentary OM record is the clear reduction in OM quantity (TOC) and quality (DCA axis 1) between 30 and 16$k cal a BP, at which point we also see an absence of preserved pollen. It is therefore likely that the site was seasonally or even permanently dry for periods of time within MIS 2. After 16$k cal a BP, we observe consistent OM preservation. The pyrolysis data suggest periods with increased input of algal lipids and increased wetland productivity (notably 9–6$k cal a BP; DCA axis 2, Fig. 7), but overall
the TOC/TN data (> 10 throughout) and the \( P_{aq} \) data suggest that the majority of sedimentary OM is terrestrial (vascular plant) in origin, and at no stage was the wetland a truly aquatic environment. The preservation of relatively labile OM components (notably cellulose and lignin) is generally poor throughout the record, with the exception of the most recent sediments and the period 9–6k cal a BP (Carr et al., 2010), suggesting oxic conditions, which would have been required in particular for the rapid microbially mediated breakdown of macromolecule OM (Bourdon et al., 2000; Carr et al., 2010). The period 9–6k cal a BP is associated with a substantial increase in the abundance of algal lipids and prist-1-ene and prist-2-ene; the latter show particularly clear peaks within this period (data not shown) and were interpreted as pyrolysis products of chlorophyll – further evidence of enhanced primary production in the wetland (Carr et al., 2010). Together, the bulk parameters, py-GC/MS dataset and the leaf wax data imply that although Rietvlei was never dominated by fully aquatic vegetation, the early Holocene (11–7k cal a BP), middle to late Holocene and last 1000 years stand out as geochronologically distinct. The early and latest Holocene are probably associated with the most productive wetland conditions, and more humid climatic conditions overall, while the middle to late Holocene was seemingly associated with a less productive wetland in which OM preservation was more restricted. Taken at face value, the \( \delta^{13}C_{TOC} \) data (Fig. 7) emphasize the site’s position within a transitional area encompassing fynbos, renosterveld, coastal thicket/strandveld and karroid elements (Vogel et al., 1978; Cowling, 1983), but such regional-scale interpretations must be tempered by the undoubtedly large (and variable) contribution of local wetland vegetation to the sedimentary OM (Carr et al., 2015). With the exception of three negative excursions, \( \delta^{13}C_{TOC} \) is relatively constant (~22‰). The most sustained excursion occurs between nine and 6k cal a BP (~26%), a period of inferred enhanced productivity. This shift in \( \delta^{13}C \) was hypothesized to reflect increased delivery of allochthonous OM from the fynbos-dominated vegetation surrounding the wetland during periods of increased humidity (Carr et al., 2010). In light of the now-available pollen data (specifically the strong coincident peaks in Proteaceae), the original interpretation by Carr et al. (2010) is supported. The higher resolution \( \delta^{13}C_{TOC} \) (Fig. 7) record now available also indicated that a very similar situation (albeit shorter in duration) occurred immediately prior to 1k cal a BP and that variability of this nature may also have occurred during late MIS 3 (although the dating resolution for this section of the record is not sufficient to make more detailed observations).

**Palaeoenvironmental change at Rietvlei—Still Bay**

The Rietvlei sequence encompasses a period within which marked changes in regional palaeoenvironments are thought to have taken place, albeit with specific details and timings often poorly resolved (see Chase and Meadows, 2007). The multi-proxy record from Rietvlei provides a first detailed archive of such changes for the southern Cape coastal lowlands. Given the climatic setting of this region, the nature and timing of these changes have important implications for the overall southern Cape year round/winter rainfall zone, and thus regional hemispheric palaeoclimatic conditions.

**MIS 3 (~35–30k cal a BP)**

The geochemical, palynological and biomarker evidence indicates that, although wetland conditions prevailed at the site, the system was not very productive. For this section, two issues should be kept in mind: (i) it was not possible to construct a reliable age–depth model with the available data, and the unit should be considered as a snapshot of conditions in the period ~35–30k cal a BP; and (ii) sea-level at this time was substantially lower than present (~80m as per Waegeman et al., 2002), which would have resulted in a lower water table. Wetland development at the site would have thus relied much more heavily on direct rainfall than it would have after ~9–7k cal a BP (Carr et al., 2006a,b). This latter point is particularly relevant when considering the fossil assemblage, wherein the presence of *Pseudoschizaea* shells/spores within sediments could in some instances indicate local seasonal drying (Scott, 1992). Indeed, the combination of increased succulents and drought-resistant taxa, the very prominent peak in *Pseudoschizaea* (Fig. 5), moderate axis one and two pyrolysis DCA scores and low \( P_{aq} \) suggests a more ephemeral wetland during this period. Vegetation surrounding the vlei included a greater proportion of succulents, drought-resistant shrubs and cosmopolitan shrubs such as *Anthocereus* and *Artemisia*, probably indicating relatively cool conditions under a seasonal rainfall regime. Under these cooler conditions, low percentages of fynbos pollen, with the exception of Restionaceae, and elevated xeric taxa may reflect drier conditions. Limited tree and tall shrub elements may reflect elevated drought stress and/or a more intense fire regime, as indicated by the high charcoal concentrations. Notable environmental variation within this 30–35k cal a BP period is however apparent; near the top of this unit, lower \( \delta^{13}C_{TOC} \) values and relatively high TOC in conjunction with increased percentages of aquatics and riparian pollen suggests increased wetland productivity and better OM preservation.

Little reliable information is available regarding southern Cape palaeoenvironments during MIS 3. The evidence that does exist suggests conditions were cooler and more humid than today (Schalke, 1973; Avery, 1982; Klein, 1983, 1984; Deacon et al., 1984; Klein et al., 1999; Scott et al., 2004; Carr et al., 2006b). These conditions could perhaps be related to enhanced winter rainfall, wherein northward shifts in the STF (Peeters et al., 2004) may have resulted in an equatorward shift of the westerly storm track (Stuut et al., 2002; Chase, 2010). The Rietvlei data suggest a less productive wetland than the present, although whether this was a function of more arid environments or a lower water table cannot be fully resolved. Given this and the chronological uncertainties, the data from Rietvlei are not necessarily inconsistent with previously reported evidence for more humid MIS 3 conditions on the southern Cape.

**Late MIS 3 to late MIS 2 (~30–16k cal a BP)**

Limited wetland productivity is inferred from the presence of highly degraded OM (Carr et al., 2010) and the lack of pollen preservation during this period. Further evidence for desiccation of the wetland environment is seen in the oxidation (slight orange mottling) of the sediments within this section, which imply shallow-water conditions or subaerial exposure (Carr et al., 2010), probably under relatively drier conditions compared with the ~35–30k cal a BP period.

While high southern latitude climate dynamics appear to have resulted in more humid conditions in the WRZ, they may have had the opposite effect on the south coast (Meadows and Baxter, 1999; Chase and Meadows, 2007). Significantly lower sea levels during the Last Glacial Maximum would have resulted in an extended coastal plain that may have altered local atmospheric dynamics to the extent that an enhanced and/or expanded continental anticyclone
blocked the penetration of winter rainfall systems to the southern Cape (Cowling et al., 1999; Carr et al., 2006b). Furthermore, decreased Agulhas Current sea surface temperatures would have led to decreased advection of moisture over the adjacent coastal areas, in turn resulting in the reduced incidence of moisture-bearing systems such as cut-off lows and ridging anticyclones, which are responsible for a large proportion of present-day rainfall. Therefore, despite potential increases in winter rainfall in the WRZ, these factors together with reduced summer rainfall and a potentially markedly lower water table at this time (Carr et al. 2006a) may have resulted in increased seasonality and overall drier conditions in the southern Cape.

Last glacial–interglacial transition (~16–11k cal a BP)

The last glacial–interglacial transition is evident in the core lithology by an increase in OM preservation. The RVSB-2 pollen record recommences at 16k cal a BP with increased percentages of fynbos and wetland taxa. Fynbos at the site reflects substantial winter rainfall and/or generally cool conditions, as indicated by regional palaeotemperature reconstructions (Heaton et al., 1986; Talma and Vogel, 1992; Truc et al., 2013). This was followed rapidly by a phase of relatively dry conditions and/or higher temperatures (e.g. reduced fynbos, low aquatic/riparian taxa percentages, high percentages of ChenoAm-type pollen and peaks in charcoal) between 14.8 and 11k cal a BP (Fig. 8). This corresponds closely to a phase of lunette dune accumulation at Voelvlei (presently a perennial lake) on the Agulhas Plain, 200 km to the west (Carr et al., 2006a; Fig. 2). The decline in fynbos pollen after ~16k cal a BP may be related to the warming evidenced at Pakhuis Pass, in the Cederberg Mountains of the Western Cape (Scott and Woodborne, 2007a,b), with both sites responding to the build up of heat in the southern oceans as a response to reductions in Atlantic Meridional Overturning Circulation during Heinrich stadial 1 (Broecker, 1998; Stocker, 1998; Stocker and Johnsen, 2003).

The Holocene (~11–0k cal a BP)

For the early Holocene, ~11–9k cal a BP, TOC remains relatively low, but the py-GC/MS data suggest steadily improving OM preservation and, after 9k cal a BP, major changes in the environment at the site are evident from every measured proxy. Most notable is the significantly enhanced wetland productivity, as indicated by substantial increases in TOC, overall OM preservation and greater proportions of algal-derived OM (DCA axis 2). This is particularly associated with the period 9–6k cal a BP, which is characterized by a prominent phase of lower δ13C TOC, accompanied by elevated aquatic/riparian pollen (Fig. 8). This period of greater productivity and likely permanent inundation (implied by the OM preservation) is the most distinct phase of the geochemical record and implies a substantial shift in the status of the wetland. It is, however, important to consider these changes in the context of regionally rising sea-levels. Regional evidence indicates increased marine influences and high mid-Holocene sea-levels at estuarine sites in the Western Cape (Compton, 2001; Carr et al., 2015) and southern Cape (Reddinger, 1988) from ~8.5 to 4k cal a BP. As elsewhere along the coast, this transgression would have raised the water table at Rietvlei (Carr et al., 2006a,b) and potentially contributed to the establishment of a more permanent wetland. Sea-level changes during the early Holocene, while not negligible, are generally thought to have been on the order of 1–3 m (Compton, 2001; Bateman et al., 2004) and their impact on the Rietvlei record during the Holocene is likely to have been less significant than during the late Pleistocene.

Within the context of the Holocene sequence, pollen evidence suggests the period ~11–9k cal a BP was generally cool (elevated fynbos pollen), but variable, and relatively mesic and/or less seasonal (low percentages of succulent/drought-resistant taxa and charcoal concentrations). From 9 to 8k cal a BP, increases in both succulent/drought-resistant taxa and charcoal concentrations indicate slightly less and/or more seasonal precipitation, but apparent contradictions exist within the aggregate dataset. Proteaceae pollen is relatively abundant during this period, coincident with the reduction in δ13C TOC (Fig. 8), and geochemical proxies suggest a perennial wet and productive wetland. Evidence from Elands Bay Cave in the south-western Cape (Klein and Cruz-Uribe, 1987; Klein, 1991; Parkington et al., 2000) indicates that this may be a transitional period, with progressively drier conditions being attributed to a decline in winter rainfall (Chase and Meadows, 2007), and the evidence from Rietvlei may be reflecting – with lags and sensitivities specific to individual proxies – a transition from a cool, wet early Holocene to warmer and drier mid-Holocene climates (Chase and Meadows, 2007).

The period from 6 to 2k cal a BP shows distinct changes in pollen composition, with notable reductions in Proteaceae, some of the aquatic/riparian pollen types, ChenoAm-type and, towards the top of the zone, Poaceae. Charcoal peaks between 7 and 5k cal a BP and then becomes less abundant until 2k cal a BP, while OM preservation is relatively poor, and δ13C is relatively high for the Holocene. Elsewhere, after ~7k cal a BP, evidence for drier conditions has been inferred from across the region, including Elands Bay Cave (Klein and Cruz-Uribe, 1987; Klein, 1991; Parkington et al., 2000), Klaarfontein (Meadows and Baxter, 2001), Cecilia Cave (Baxter, 1989) and Pakhuis Pass (Scott and Woodborne, 2007a,b) in the west, and Boomplaas Cave (Scholtz, 1986), Norga (Scholtz, 1986), Groenvlei (Martin, 1968) and Vankervelsvlei (Irving, 1998) in the south. Recent high-resolution stable isotope records obtained from rock hyrax middens from Seweweekspoort (Chase et al., 2012, 2013) better constrain this period of relative aridity as a significant anomaly occurring between 7.0 and 5.0k cal a BP, and being linked to reductions in Antarctic sea-ice extent (Fischer et al., 2007) and the position of the westerly storm track (Lamy et al., 2001) (Fig. 8). Data from Rietvlei–Still Bay (e.g. prominent charcoal peaks between 7.0 and 5.5k cal a BP and reduced OM preservation) also suggest that the mid-Holocene was characterized by warmer and drier conditions. Some sites at the transition between winter and aseasonal rainfall zones, such as Kathbakkies Pass (Meadows et al., 2010; Chase et al., 2015) and ByneskranSkop (Avery, 1993), have provided evidence indicating increases in summer, and generally more mesic conditions during the middle Holocene, but at Rietvlei such increases in humidity are not clear from the data available.

The late Holocene at Rietvlei begins with a period of relatively low charcoal concentrations from 5.0 to 3.3k cal a BP, reduced fynbos abundance, and an increase in afromer盼 and thicket pollen, which may correspond to the phase of renewed forest development at Norga (Scholtz, 1986), and more humid conditions at Seweweekspoort (Chase et al., 2013), an equatorward shift of the westerlies (Lamy et al., 2001) and generally more mesic conditions with reduced rainfall seasonality (Chase and Meadows, 2007). In contrast, between ~3 and 1k cal a BP, a strong increase in charcoal concentrations is observed at Rietvlei. This coincides with
Fig. 8. Comparison of selected Rietvlei–Still Bay variables and regional proxy evidence. (A) Iron concentrations from the Chilean continental margin at 41°C (Lamy et al., 2001). (B) Sea salt sodium concentrations from the EPICA DML ice core in Antarctica (Fischer et al., 2007). (C) The sum of the fynbos pollen taxa percentages in the Rietvlei–Still Bay core. (D) The Rietvlei–Still Bay δ13C record. (E) Microscopic charcoal concentrations from the Rietvlei–Still Bay core. (F) The sum of succulent and/or drought-resistant pollen taxa percentages in the Rietvlei–Still Bay record. (G) The sum of afrotropical forest and coastal thicket taxa percentages in the Rietvlei–Still Bay record. (H) The sum of aquatic and riparian pollen taxa percentages in the Rietvlei–Still Bay record. (I) Detrended correspondence analysis factor 1 scores from Carr et al. (2010). (J) Detrended correspondence analysis factor 2 scores from Carr et al. (2010). (K) Sea surface temperature (SST) stack from the precursor/upstream region of the Agulhas Current (marine core MD962048) (Caley et al., 2011b). (L) The δ15N record from the Seweweekspoort-1-5 hyrax midden (Chase et al., 2013).
slightly drier conditions at Seweweekspoort, indications for a poleward shift of the westerris, drier conditions at Norga and phases of lunette accumulation at Voëtvlei and Buffels-jacht Pan (2.8–2.5 and 1.25 ka) on the Agulhas Plain (Carr et al., 2006b). A strong fynbos presence during this latter period may suggest that conditions were generally cool, probably still with significant winter rainfall, but increased rainfall seasonality may have elevated fire frequencies and promoted the development of fynbos taxa over fire-prone afrotemperate and thicket elements (Fig. 8). Note that these findings differ from interpretations of the pollen record from Princess Vlei, on the Cape Peninsula (Neumann et al., 2011). Incorporating refinements on the published linear age model using Bacon (version 2.2) (Blauw and Christen, 2011), the period of wetter conditions inferred from changes in Factor 2 of the authors’ principal components analysis occurs between 3.5k and 2.1k cal a BP. Whether the opposing trends reflect local conditions and/or distinct sensitivities to factors such as sea-level change remain to be more explicitly explored.

In the last thousand years, charcoal concentrations and fynbos pollen percentages decrease significantly (Fig. 8). Succulent and drought-resistant taxa also become less abundant, and in accord with evidence at Norga for forest expansion (Scholtz, 1986), afrotemperate forest taxa increase markedly in the RVSB-2 record. The substantial increases in Cyperaceae and Poaceae during that last 1k cal a BP are perhaps indicative of the development of the contemporary floating vegetation mat, a process that seemingly occurs in conjunction with increased abundances of several aquatic pollen types and increased P_ad/flower ACL/lower CPI. Combined, these suggest a shift to a more advanced hydroseral phase in response to increased moisture availability and perhaps a more aseasonal rainfall regime. The decline in fynbos taxa is inconsistent with inferences of increased winter rainfall in the south-western Cape over the last 1500 years based on diatom data from Verlorenvlei (Stager et al., 2012). This may be due to the spatial complexity of the south-western Cape or it may be that increased summer rainfall during this period resulted in more mesic conditions, which suppressed fire frequencies and favoured the expansion of afrotemperate and thicket taxa at the expense of fynbos.

Conclusions

We present a multi-proxy record derived from the Rietvlei-Still Bay wetland, which reveals that considerable palaeoenvironmental change has taken place along the southern Cape coast during the late Pleistocene and Holocene. The results of the pollen analysis suggest that there were significant vegetation community reorganizations within this important region of the Fynbos Biome/Cape Floristic Region. Fynbos was particularly dominant within the Lastglacial period (~16k cal a BP), the early Holocene (~11–8k cal a BP) and from 2.2 to 0.9k cal a BP, and its presence shows some commonalities with the relative influence of the westely systems, as recently reported in other high-resolution records. Succulent/drought-resistant and more cosmopolitan elements characterized the MIS 3 section (~35–30k cal a BP) as well as the mid-Holocene (6.9–3.3k cal a BP), while coastal thicket and afrotemperate forest were the dominant vegetation types for the most recent period (0.9–0k cal a BP).

Inferences from the vegetation dynamics, together with the geochemical and plant biomarker data, indicate that there were substantial changes in wetland productivity and overall moisture availability at the site. Interestingly, the stable carbon isotope (δ13C) record reveals long periods of stability punctuated by short episodes of marked reductions that correspond closely to shifts in the abundance of fynbos pollen and charcoal abundance. The Rietvlei wetland was relatively less productive than present during MIS 3 (~35–30k cal a BP) either as a function of more arid conditions and/or due to a lower water table. Drier and warmer conditions prevailed between 16 and 11.7k cal a BP and for much of the period 7–3.3k cal a BP. Relatively more humid and cooler conditions together with enhanced winter rainfall were associated with the early Holocene (11.7–7k cal a BP) and the period 2.2–0.9k cal a BP. The establishment of a more aseasonal rainfall regime coupled with higher temperatures took place from 0.9k cal a BP to the present.

Being influenced by a variety of factors including rainfall amount and seasonality, atmospheric and oceanic temperatures, atmospheric CO2, sea levels and ocean currents, the southern Cape coast’s climatic and vegetation histories are complex. Despite this, several aspects of the RVSB record are consistent with the regional palaeoenvironmental record and suggest that the relative dominance of different moisture-bearing systems has greatly influenced the region.

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Abbreviations. ACL, average chain length; CPI, carbon preference index; DCA, de-trended correspondence analysis; DCM, dichloromethane; MIS, Marine Oxygen Isotope Stage; OM, organic matter; OSL, optically stimulated luminescence; py-GCMS, pyrolys-is-gas chromatography/mass spectrometry; STF, Subtropical Front; TN, total nitrogen; TOC, total organic carbon; YRZ, year-round rainfall zone.

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