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Late Quaternary climatic changes revealed by luminescence dating, mineral magnetism and diffuse reflectance spectroscopy of river terrace palaeosols: a new form of geoproxy data for the southern African interior

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ABSTRACT

The nature, spatial patterns and forcing mechanisms of Quaternary climatic changes across southern Africa remain unresolved and contentious, principally due to the scarcity of continuous and robustly-dated proxy records. We present what we interpret to be a broadly continuous record of late Quaternary climatic change based on optically stimulated luminescence (OSL) dating, and mineral magnetic and diffuse reflectance spectroscopy (DRS) analyses of stacked palaeosols within an overbank alluvial succession along the Modder River, central South Africa. The OSL ages indicate that alluvial sedimentation occurred at a fairly steady rate, averaging ~0.15 mm/yr from at least 44 ka until ~0.83 ka. This suggests that the palaeosols are accretionary, having formed contemporaneously with sedimentation. Climate is identified as the key soil-forming factor controlling the intensity of pedogenesis and is reflected in the changing concentration of pedogenic ferrimagnetic minerals (magnetite/maghemite) of single domain and superparamagnetic dimensions, and by variations in the amount of hematite compared to goethite. These data indicate that the climate was generally dry (rainfall ~200–400 mm/yr) from ~46 to 32 ka, except for a brief peak in humidity at ~42 ka. There was then a period of greater humidity (rainfall ~400–600 mm/yr) from ~32 to 28 ka, possibly reflecting enhanced moisture supply from the Atlantic Ocean associated with the equatorward migration and intensification of westerly storm tracks. Although the precise mechanism remains unresolved, this climatic change may have been linked to an obliquity minimum at ~29 ka. After ~28 ka, the climate became progressively cooler and drier, especially between ~18 and 15.5 ka when rainfall was as low as ~100–200 mm/yr. Temperatures and rainfall then increased from ~15.5 ka onwards, with the latter possibly linked to rising sea-surface temperatures in the SW Indian Ocean and enhanced moisture supply from easterly circulation. At ~0.83 ka, a time corresponding with part of the Medieval Climatic Anomaly (MCA, ~900–1300 AD), rainfall reached ~600–700 mm/yr and was higher than at present (~400–500 mm/yr). Fluvial landforms have previously been overlooked as a source of palaeoenvironmental information in southern Africa, but this study clearly demonstrates the potential to extract robust palaeoenvironmental data from alluvial-palaeosol successions in the arid to semi-arid interior where other forms of proxy record are scarce.

1. Introduction

The dominantly arid to semi-arid climate of interior southern Africa generally precludes the production and preservation of organic-based proxies that traditionally are used to date and reconstruct Quaternary environmental changes. The resulting scarcity of long, continuous and robustly-dated palaeoenvironmental datasets has hindered progress towards resolving the nature, spatial patterns and forcing mechanisms of Quaternary climatic changes (Chase and Meadows, 2007). Given the lack of organic-based proxies, southern African palaeoenvironmental data is largely derived from spatially pervasive geomorphological landforms such as sand dunes and palaeolake shorelines (Thomas

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and Burrough, 2012). Palaeoenvironmental information can be extracted from these so-called 'geoproxies' because their sedimentology, morphology and spatial distribution may have been controlled by past environmental (e.g. climatic) changes (Thomas and Burrough, 2012, in press; Thomas, 2013). Although our ability to robustly date dune and palaeolake geoproxies using optically stimulated luminescence (OSL) techniques has greatly advanced (Duller, 2004; Tooth, 2012), little consensus has emerged as to the interpretation and palaeoenvironmental significance of the resulting datasets (e.g. Burrough et al., 2009; Chase, 2009; Thomas and Burrough, in press). Moreover, these geoproxy datasets often conflict with other proxy datasets, which has resulted in their exclusion from some regional syntheses of late Quaternary environmental and climatic change (Chase and Meadows, 2007).

Fluvial sedimentary landforms (e.g. alluvial river terraces) offer an additional source of geoproxy data for southern Africa (e.g. Shaw et al., 1992; Verster and van Rooyen, 1999), but are yet to be investigated in any detail. This is probably due to the fact that alluvial successions are often discontinuous and robust chronologies have traditionally been difficult to establish. Nevertheless, despite some ambiguities in interpretation, studies in other dryland locations have demonstrated the potential of fluvial systems to record palaeoenvironmental changes (e.g. Nanson and Tooth, 1999; Tooth, 2007; Reid, 2009). There is considerable opportunity to address this research deficiency in interior South Africa, particularly where extensive river channel and donga (gully) incision (Tooth et al., 2004; Keen-Zebert et al., 2013; Lyons et al., 2013) has resulted in widespread alluvial exposures. In many cases, alluvial exposures reveal detailed stratigraphy, palaeosols and archaeological remains that may be of palaeoenvironmental significance (e.g. Butzer, 1971; Verster and van Rooyen, 1999; Churchill et al., 2000; Tooth et al., 2013). To explore this opportunity, this paper focuses on the site of Erfkroon, situated along the middle reaches of the Modder River, western Free State, central South Africa (Fig. 1). Here, deep river channel and donga incision has exposed an ~15 m thick alluvial succession, with the uppermost ~8 m hosting four stacked palaeosols (Tooth et al., 2013). These palaeosols contain rich and diverse fossil faunal (e.g. extinct and extant wetland, aquatic and grassland species), as well as archaeological assemblages, including lithics associated with the African Middle (~240–25 ka) and Later (~25 ka to historic times) Stone Ages (Churchill et al., 2000). Although Tooth et al. (2013) previously used infrared stimulated luminescence and OSL dating techniques to establish the late Quaternary antiquity of the overbank succession (last ~42 ka), the chronology was of insufficient resolution for detailed investigations of the palaeosols. If the palaeosols contain palaeoclimatic signatures, however, this provides an opportunity to elucidate the nature of palaeoclimatic changes in a region of interior southern Africa notably devoid of robust palaeoenvironmental datasets. In particular, given its location in central South Africa, Erfkroon may help to clarify the dynamic interplay between westerly (Atlantic Ocean) and easterly (Indian Ocean) atmospheric circulation systems during the Quaternary, both of which are key determinants of moisture supply to the interior of southern Africa (Chase and Meadows, 2007; Gasse et al., 2008).

In a range of environmental settings, mineral magnetic measurements of palaeosols have helped to reconstruct palaeoclimatic changes. This is best exemplified by studies of loess-palaeosol

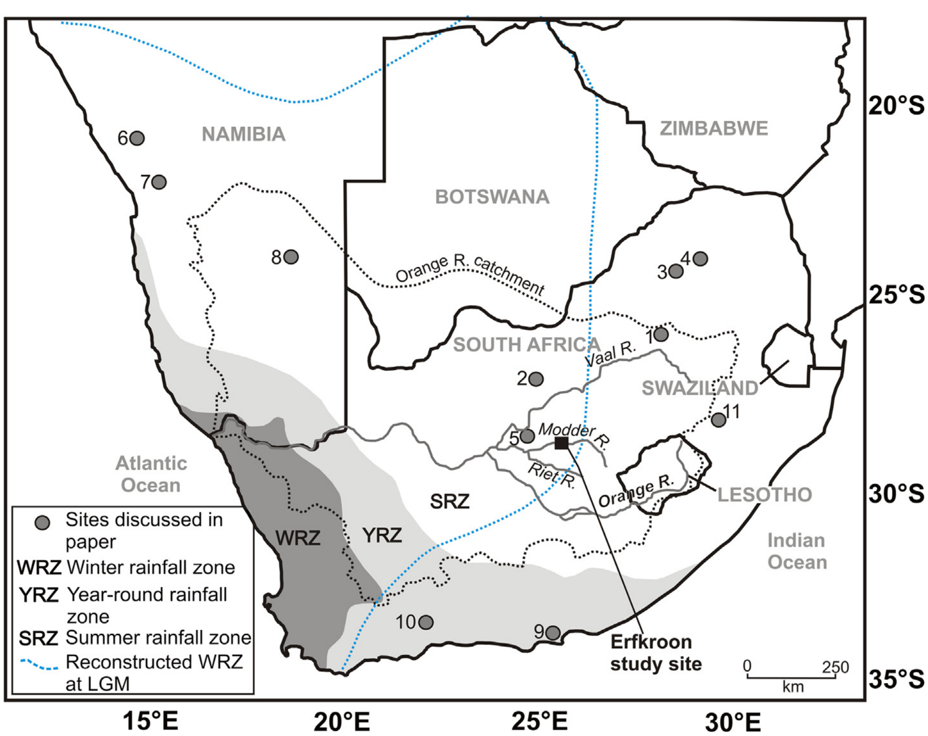

Fig. 1. Map showing the location of the Modder River within the Orange River catchment (black dotted line) and the location of the Erfkroon study site (28°52′09.2″S, 25°35′40.7″E) along the middle reaches of the Modder River. The present extent of the winter rainfall zone (>66% of mean annual rainfall falls between April–September), summer rainfall zone (>66% of mean annual rainfall falls between October–March) and year-round rainfall zone is shown (Chase and Meadows, 2007). The blue dashed line indicates the reconstructed position of the winter rainfall zone during the Last Glacial Maximum (LGM), as proposed by Chase and Meadows (2007). Sites referred to in the text are also shown: 1) Lake Tswaing (Partridge et al., 1997; Schmidt et al., 2014); 2) Equus Cave (Johnson et al., 1997); 3) Wonderkrater (Scott et al., 2003; Truc et al., 2013); 4) Cold Air Cave (Lee-Thorp et al., 2001; Holmgren et al., 2003); 5) Alexandersfontein (Butzer et al., 1973; Butzer, 1984); 6) and 7) Austerlitz and Spitzkoppe hyrax middens, respectively (Chase et al., 2009, 2010); 8) Stampriet aquifer (Stute and Talma, 1998); 9) Uitenhage aquifer (Stute and Talma, 1998); 10) Boomplaas Cave (Thackeray, 1990); and 11) Braamhoek wetland (Norström et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)