PERGAMON

Quaternary Science Reviews 21 (2002) 1571–1576

QSR RAPID COMMUNICATION

Rapid Communication

Variation of soil magnetism across the Russian steppe: its significance for use of soil magnetism as a palaeorainfall proxy

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Received 11 January 2002; accepted 7 April 2002

Abstract

Modern soils across the Chinese Loess Plateau exhibit strong but disputed correlation between their pedogenic magnetic content and annual rainfall. A soil magnetism/rainfall transfer function could provide a quantitative proxy of Quaternary rainfall for this region. However, some argue that 'magnetic dilution', through spatially varying fluxes of weakly magnetic dust, controls the soil magnetic properties. Here, we test the soil magnetism/rainfall couple by examining 22 Russian steppe soils (free of present dust accumulation) across a climatic transect. From the semi-arid Caspian region to the more humid Caucasus, the soils display systematic increases in topsoil ferrimagnetic concentrations. With the exception of climate (and its co-variant, vegetation), soil-forming factors are essentially constant across this stable area. Hence, the soil magnetic variations dominantly reflect climate and from statistical analysis, principally rainfall. Further, the Russian steppe magnetic/rainfall relationship matches that observed for the Chinese Loess Plateau. These independent data thus substantiate the soil magnetism/rainfall climofunction and, by inference, eliminate 'dust dilution' as a significant magnetic factor. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Soil magnetism is an increasingly important natural source of climatic and environmental information. Critically, the pedogenic magnetic content of well-drained, buffered and unpolluted soils appears to reflect dominantly the influence of climate, and specifically, rainfall (Maher et al., 1994; Han et al., 1996; Maher, 1998). Testing of the robustness of this climate/magnetism relationship is important, as it has been used as a quantitative proxy of Quaternary rainfall variations, through magnetic analysis of the >30 palaeosols interbedded within the famous Chinese loess sequences (Maher et al., 1994). The magnetism–climate couple was first observed for modern soils developed on the near-horizontal, homogeneous substrates of the Chinese Loess Plateau (Maher et al., 1994; Liu et al., 1995), where annual rainfall is $\sim 300\,\mathrm{mm\,yr^{-1}}$ in the west, $\sim 550\,\mathrm{mm\,yr^{-1}}$ in the central Plateau and $\sim 700\,\mathrm{mm\,yr^{-1}}$ in the south. Maher et al. (1994) examined, for a relatively small sample set, the relationships between pedogenic magnetic susceptibility and modern climate variables. Magnetic susceptibility (a measure of the 'magnetisability' of a material) is dominated in these soils by the presence of small amounts ($\sim 0.3\%$) of magnetite and its oxidized counterpart, maghemite, of ultrafine-grain size ($\lesssim 30\,\mathrm{nm}$). The pedogenic susceptibility (χ_{ped}) was defined as the maximum susceptibility value (χ) of the B horizon minus the χ of the parent loess. Maher et al. (1994) found strong positive correlation ($R^2 = +0.94$) between the logarithm of pedogenic χ and annual rainfall. Subsequently, Han et al. (1996) examined a further 63 topsoil samples across the Loess Plateau and confirmed the direct relationship between rainfall and pedogenic susceptibility (but calculated polynomial rather than logarithmic relationships between susceptibility, rainfall and temperature). Conversely, Porter et al. (2001) claim that 84% of the modern susceptibility variance is due to 'dilution effects' resulting from spatial variations in the accumulation rates of weakly magnetic loess, and only 10–11% due to the influence of rainfall. Here, we test the

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PII: S0277-3791(02)00022-7

soil magnetism/climate relationship for the first time in a geographically independent region, by examining the magnetic properties of 22 modern soils from a transect spanning the Russian steppe from the N. Caucasus to the Caspian Sea. Climate data for the last $\sim$100 yr are available from stations across this loessic steppe.

2. Sites and methods

The sampled transect spans $\sim$1000 km, across the loess-mantled, exhumed marine plain from the northern flanks of the Caucasus to the northwestern margins of the Caspian Sea (Fig. 1). This remote region is characterized by low topography, continuous and undisturbed grassland cover, geomorphic stability (i.e. absence of any loess accumulation at the present day) and absence of pollution sources. The soils are light or dark kastanozems (FAO/UNESCO classification): well-drained soils with brown (7.5YR 5/4–10YR 3/3) Ah horizons (with >50% of roots concentrated in the upper 25 cm) overlying a brown to cinnamon (7.5YR 5/2–10YR 5/3), argic (clay-enriched) or cambic (slightly weathered) B horizon, often with carbonate and/or gypsum accumulation in or below the B horizon. pH values vary between 7.2 and 8.2. The regional climate is characterized by a marked gradient in precipitation, from $\sim$500 mm yr^{-1} for the Stavropol region (Caucasus margins) to $\sim$300 mm yr^{-1} around Volgograd (Caspian lowlands), with precipitation distributed through the year (Fig. 1). Temperatures vary from $\sim -5°C$ to $-10°C$ in winter to $\sim 25°C$ in summer; $\gtrsim$170 days yr^{-1} have temperatures exceeding 10°C (State Meteorological Organisation, 1966, 1968). Samples were obtained by hand augering to a depth of 2 m; three soil cores were taken within a 5 m radius at each sample location. Field measurements of magnetic susceptibility were made on each core; highest values were always within the upper 40 cm, decreasing rapidly to a minimum for the parent loess.

In the laboratory, samples were taken at 10 cm intervals from the top 40 cm of each profile, together with a sample of parent material from 150–180 cm depth, dried at 40°C and packed into 10 cc polystyrene sample holders. Magnetic measurements made on each sample (using the methods outlined by Maher et al., 1999), included: low- and high-frequency magnetic susceptibility, anhysteretic remanence and incremental remanence acquisition.

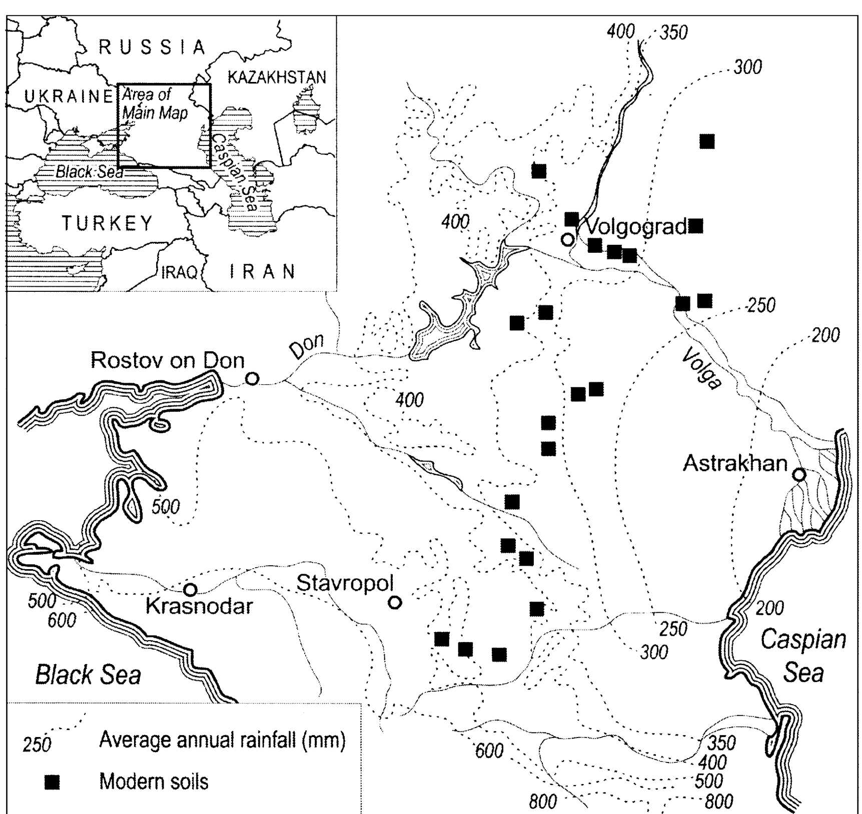

Fig. 1. Location map, showing sample sites and regional isohyets (annual rainfall in mm yr^{-1}).

3. Results

As shown in Fig. 2, magnetic susceptibility values range from ~ 10–$20 \times 10^{-8}\,m^3\,kg^{-1}$ in the C horizons, to a maximum of $\sim 95 \times 10^{-8}\,m^3\,kg^{-1}$ within the A horizon of Profile A99-11. (As a first approximation, these values indicate a magnetite concentration of up to 0.04% in the substrate and $\sim$0.2% in the most magnetic topsoil). Susceptibility maxima always occur within the upper 40 cm of the soil profiles; values fall rapidly below this depth. Values of frequency-dependent susceptibility (normalized to the low-frequency value) range from 0–3% in the parent substrate but rise to 5–12% in the A and B horizon samples. At the frequencies of measurement used here (470 and 4700 Hz), the high values of the A and B horizons are contributed by ferrimagnetic grains that are so fine-grained ($\lesssim$20 nm) as to be superparamagnetic (SP) at room temperature (e.g. Dunlop, 1981; Maher, 1988; Dearing et al., 1996). Low values, as for the C horizons, indicate either a scarcity of such grains and/or the presence of coarser-grained, multidomain ferrimagnets ($\gtrsim 1\,\mu m$).

All of the C horizon samples, consisting of loessic parent material, exhibit similar patterns and magnitudes of acquisition of room-temperature magnetic remanence (IRM). They acquire very little remanence below 10 mT, $\sim$50% of their total IRM between 10 and 100 mT, and the remaining $\sim$40% at high applied fields, from 300 to 1000 mT (Fig. 3). Such high applied fields are required to magnetise the weakly magnetic materials, haematite and goethite, whilst strongly magnetic magnetite and maghemite acquire most of their magnetization in fields less than 100 mT. The maximum IRM values for the C horizons range narrowly around $2.2 \times 10^{-3}\,Am^2\,kg^{-1}$. In contrast, the A and B horizon samples acquire significantly more of their remanence at low fields (up to 10% at fields $<$10 mT), up to 70% at fields between 10 and 100 mT, and 15–30% at fields in excess of 300 mT. In absolute terms, they also contrast with their parent samples, displaying saturation IRM (SIRM) values 2–3 $\times$ larger (Fig. 3). The majority of the A and B samples also show higher high-field remanence (HIRM) values. This contrast between A and B horizons and parent substrates is maintained when their anhysteretic remanence (ARM) is examined. ARM values are highest for interacting single domain ferrimagnets ($\sim$30–50 nm), such as the chains of magnetic particles made intracellularly by magnetotactic bacteria, and moderately high for equally fine-grained but less organized grains observed in magnetically enhanced soils (Özdemir and Banerjee, 1982; Maher, 1988; Maher et al., 1999). The ARM values of the C horizon samples are low and clustered, in comparison with the higher and broader range of values exhibited by the upper soil samples (Fig. 4).

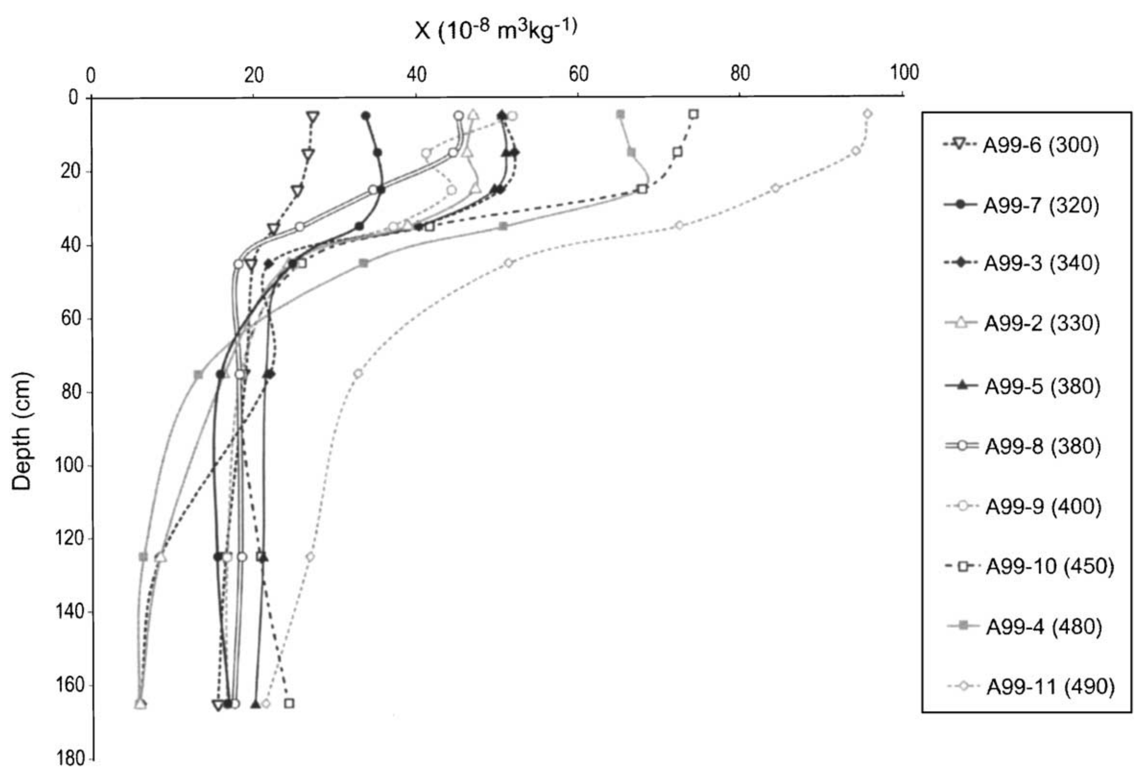

Fig. 2. Magnetic susceptibility versus depth for 10 representative soil profiles spanning the geographic transect; annual rainfall values (in brackets, mm yr^{-1}) are also given.

4. Discussion

Magnetic analysis of these modern, kastanozem-type soils shows that they contain varying amounts of ultrafine-grained ferrimagnets. Whereas the parent substrates of the soils are uniformly weakly magnetic, A and B horizons contain significant additional concentrations of magnetite and maghemite. The pedogenic magnetic content of the soils (e.g. magnetic susceptibility$_{\mathrm{A,B\ horizon}}$−magnetic susceptibility$_{\mathrm{C\ horizon}}$) varies across the modern rainfall gradient (Fig. 5), being at a minimum for the semi-arid zone close to the Caspian Sea ($\sim$300 mm rain yr^{-1}) and rising to a maximum for the more humid zone close to the N. Caucasus region ($\sim$500 mm rain yr^{-1}). Examining the relationships between the soil transect magnetic properties and the major climate variables, the strongest statistical relationships exist between annual rainfall and χ_{LF} and χ_{ARM} (correlation coefficients of 0.93), and between summer rainfall and χ_{LF} and χ_{ARM} (correlation coefficients of 0.85 and 0.84, respectively).

Applying to this region Dokuchaev's (1883) soil-forming factors, via Jenny's classic (1941) equation, it can be seen that parent materials are essentially homogenous (well-mixed loess), topography is muted and duration of soil formation apparently constant (critically, no loess is accumulating here at the present day). Hence, as vegetation will co-vary with climate, the equation can be reduced in this region to a climofunction. That is, the soil properties—including their magnetic properties—vary mostly as a function of climate, and, as shown by regression analysis, principally as a function of annual rainfall. These new steppe magnetic data thus substantiate the magnetism/rainfall relationship previously observed in the Chinese Loess Plateau (Fig. 5). By inference, the close correspondence between the magnetic/climate relationships from these two disparate regions suggests strongly that the so-called 'dust dilution' effect (proposed to account for

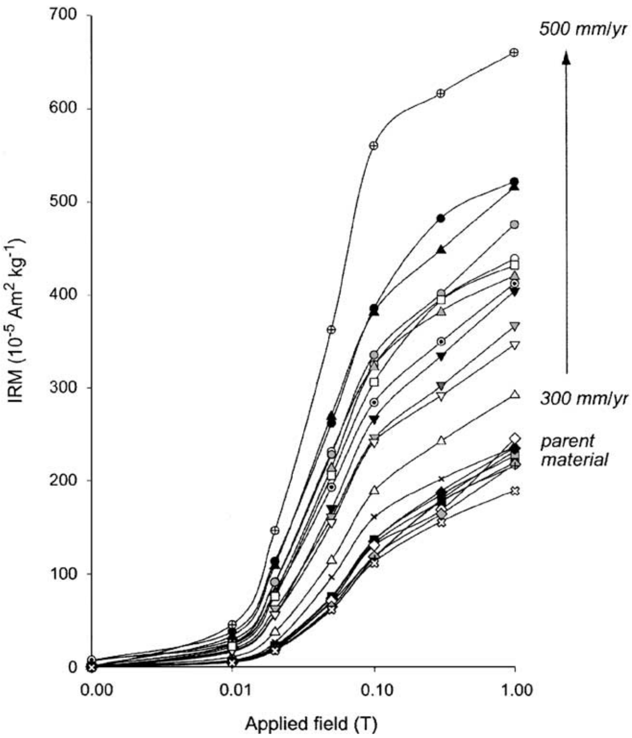

Fig. 3. IRM acquisition behaviour for parent materials and A and B horizons, together with trend of annual rainfall data.

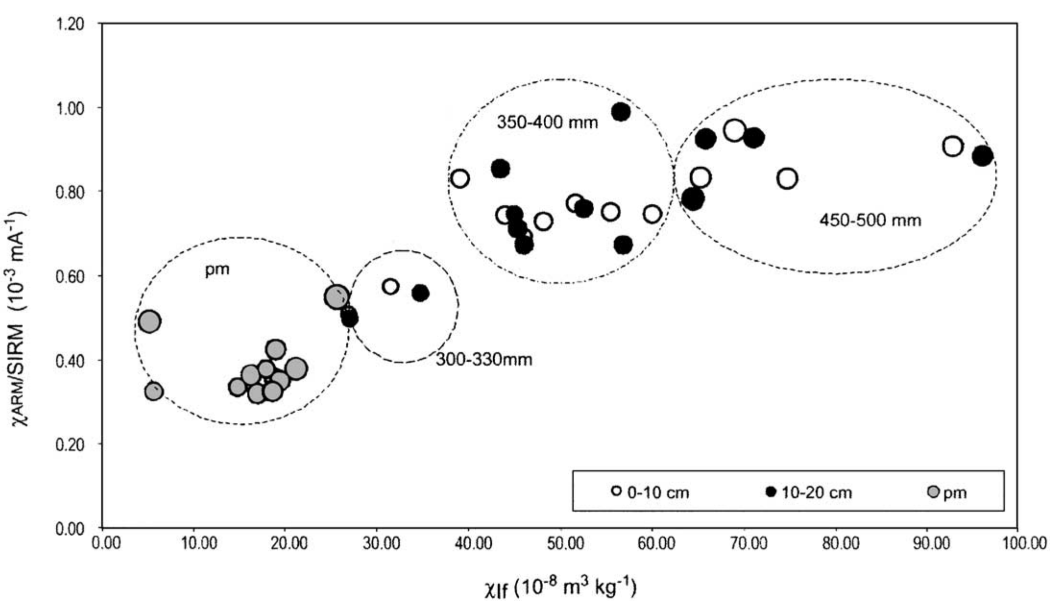

Fig. 4. χ_{ARM} (normalized with respect to the SIRM) versus χ data, C horizons and A and B horizons, together with rainfall ranges.

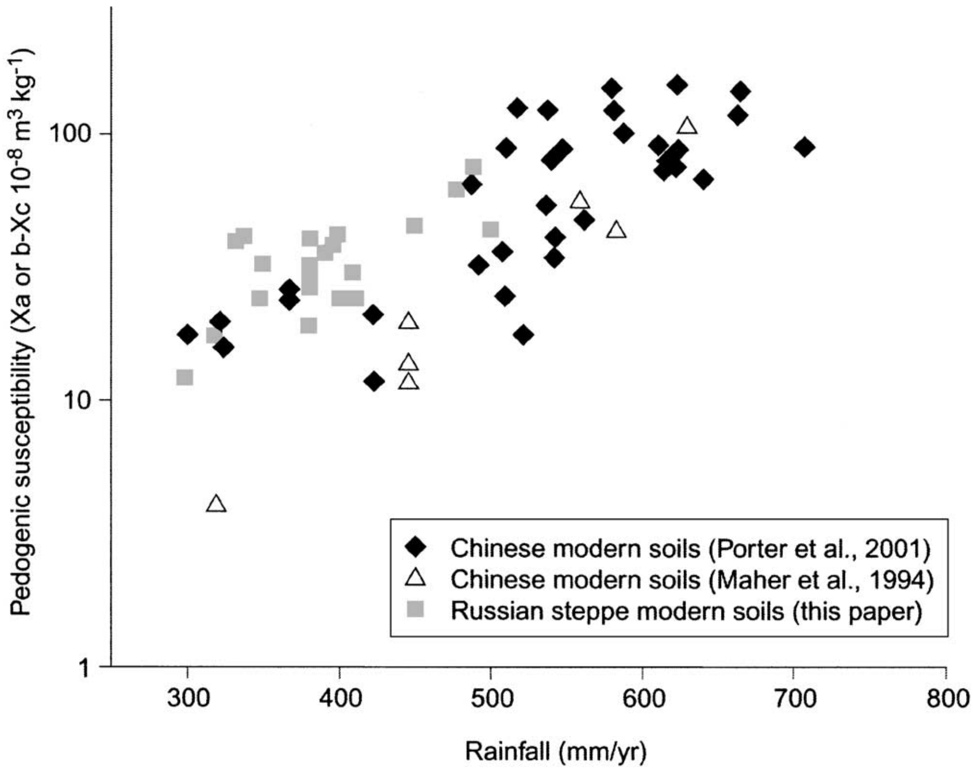

Fig. 5. Pedogenic susceptibility ($\chi_{topsoil} - \chi_{C\ horizon}$) versus annual rainfall: Russian steppe transect and published Chinese Loess Plateau data. A χ value of $20 \times 10^{-8}\,m^3\,kg^{-1}$ has been used for the C horizon of the Chinese Loess Plateau modern soils (i.e. the χ value of the least-weathered loess unit).

most of the magnetic variance across the Chinese Loess Plateau) is not a significant factor. The relationship between soil magnetism and climate is unsurprising, given that other soil iron oxides demonstrate climate dependence (e.g. the goethite–haematite ratio in soils varies systematically along climosequences, Schwertmann, 1988). Laboratory experiments show that any of the soil iron oxides can be formed via oxidation of an initial mix of Fe^{2+}/Fe^{3+} in suspension; the species and grain size formed depends on the experimental conditions, particularly pH, oxidation rate, and Fe concentrations (Taylor et al., 1987). Formation of goethite, rather than magnetite, seems to be favoured by higher oxidation rates and lower pH (Taylor et al., 1987). Formation of haematite is favoured by higher temperatures and decreased water activity (Schwertmann, 1988). In these loessic soils, it seems likely that Fe^{2+} is supplied during periods of soil wetness via the activity of iron-reducing bacteria (Starkey and Halvorson, 1927; Munch and Ottow, 1980; Maher and Thompson, 1995). Intermittent wetting and drying of soils would favour magnetite formation, whilst longer periods of dryness favour information of the more oxic iron compounds, haematite and goethite. Thus, competitive feedback between formation of ferrimagnets and their subsequent loss by oxidation may result in soils reaching a rainfall (rather than temperature)-determined equilibrium magnetic value (Maher, 1998).

5. Conclusions

1. Kastanozem-type soils across a ~1000 km transect of the loessic steppe between the N. Caucasus and the Caspain Sea display enhanced ferrimagnetic concentrations in their A and B horizons compared with their homogenous, weakly magnetic parent substrates. The soils display systematic increases in their topsoil magnetic properties from the semi-arid to the more humid end of the transect. As a first approximation, the magnetic measurements indicate that concentrations of magnetite/maghemite are up to 5 × higher in the topsoils than the parent material.
2. All the soil-forming factors, with the exception of climate (and its co-variant, vegetation) are essentially constant across the loessic Russian steppe. Thus, soil magnetic properties dominantly reflect the influence of climate. Statistical examination of the relationships between the soil magnetic properties and the major climate variables identifies annual rainfall as the most significant factor ($R^2 = 0.93$).
3. Thus, the magnetic mineralogy of these steppe soils, as with that of the modern soils of the

dust-accumulating Chinese Loess Plateau, appears to reflect present-day rainfall variations. The demonstrated coupling of the soil magnetism of the modern steppe soils—unaffected by any dust dilution effects—with present-day climate provides and substantiates a quantitative transfer function which enables reconstruction of *past* rainfall variations from the magnetic properties of well-drained loessic palaeosols across and beyond this region. Such quantitative proxies for palaeorainfall are rare and are essential for testing both of postdictions and predictions of climate models, either global or regional in scale.

Acknowledgements

We are very grateful for the financial support from the NATO Science Programme and the Russian Foundation for Basic Research, which enabled this project to be carried out.

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