

Palaeoecological evidence of pollen sequence in eastern Spain challenges existing concepts of vegetation change

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Palaeoecological evidence from a pollen sequence in eastern Spain does not support the notion of potential vegetation as employed by the floristic-phytosociological approach of vegetation classification. A middle Holocene replacement of *Pinus* forest by *Quercus*-dominated communities is interpreted as the result of increased fires in the surroundings of the site and suggests that sclerophyllous scrub in the region could not have been determined by climatic conditions as previously assumed. Therefore it cannot be considered to be a climax state of vegetation. The possible role of anthropogenic and random processes in this change should not be underestimated.

The concept of potential vegetation has become one of the most established notions in vegetation science. This concept, employed since the early 20th century by the so-called floristic-phytosociological, or Braun-Blanquet, approach,¹ assumes the existence of stable equilibrium conditions that can be identified on the basis of climatic and edaphic factors. The concept is also based on the idea that present-day floristically defined assemblages established along spatial gradients can be used to infer temporal patterns of succession.² While there are worldwide debates in ecology³ about dilemmas such as the nature of vegetation boundaries and the character of continuous/discontinuous ordering of communities along topographical gradients, stability *vs* instability of the syntaxonomic system, and determinism *vs* indeterminism, the floristic approach continues to dominate the literature on vegetation science published in Europe and it has relevance to other regions such as South Africa⁴ and, more recently, the United States.^{5,6} In Spain, for instance, this approach forms the bulk of the teaching content of geobotany and biogeography in most university courses. However, the foundations of the floristic approach are far from consistent. Here we present a palaeoecological sequence obtained from eastern Spain that provides evidence for rejecting the notion of potential vegetation. Our arguments are based on developments in the fossil record and not on the current vegetation at the site, which has mainly been replaced by cultivation.

A synthetic palaeoecological record of the Navarrés peatbog, eastern Spain (39°06'N, 0°41'W), is shown in Fig. 1. It is based on a micro- and macroscopical analysis of 192 samples, a 2.5-m sequence at 1-cm intervals. One hundred and eighty-eight palynological types, two types of Characeae gyrogonites, 19 seed types and three size classes of charcoal particles were

identified.⁷ The sequence is subdivided in four biozones. The basal zone N3PA (c. 31 000–27 000 yr BP), with abundant *Quercus* along with many indicators of Mediterranean landscape, shows the clearest evidence for an expansion of thermophilous vegetation in Spain during an interstadial of the last glacial period. This expansion of thermophilous taxa may have originated from nearby coastal and intra-mountainous glacial refugia.^{8,9} The zone N3PB (c. 27 000–10 000 yr BP), characterized by *Artemisia*, Chenopodiaceae and *Ephedra distachya-nebrodensis*, shows the typical xerophytic vegetation of cold glacial stages in southern Europe.^{10–12} Biotic preservation is interrupted in the basin around the last glacial maximum under the dominance of erosional processes and deposition of sands between 145 and 165 cm. The Younger Dryas cold spell is clearly evidenced in the uppermost part of N3PB and its peak dated around 10 340 yr BP. During the glacial stage recorded at Navarrés, *Pinus* is the dominant tree taxon. At the onset of the Holocene, zone N3PC (c. 10 000–6000 yr BP), there is no evidence of angiosperm colonization, and *Pinus* continues to dominate the landscape until abruptly replaced by *Quercus* and other shrubs at c. 5930 yr BP. Different species of *Quercus* expanded to form a patchy macchia- and garrigue-like landscape. This change goes with an algal succession (from *Closterium* and *Botryococcus* to *Zygnemataceae* and Characeae), and angiosperm colonization (*Typha*, Cyperaceae, *Apium*, *Juncus*), that suggests increased eutrophication and lake infilling. Along N3PD, the occurrence and distribution of large macroscopic charcoal fragments in addition to microscopic charcoal demonstrate that fires were particularly severe just before this vegetation change. It seems likely that fire is related to the appearance and establishment of *Quercus*-dominated communities. Additional evidence of fire may well come from the pollen spectra. The combination of *Quercus suber*, *Pinus pinaster*, *Erica arborea*, *Ulex parviflorus* type, *Phillyrea*, *Cistus salvifolius*, *Pteridium*, *Ruta*, *Fumaria*, *Euphorbia*, and *Anagallis arvensis*, among others⁷, strongly suggests post-fire vegetation dynamics similar to that found in studies of experimental plots.¹³

According to climatic and soil features¹⁴, the potential vegetation, that allegedly existing in the absence of anthropogenic interference, has been assumed to be an evergreen oak forest dominated by *Quercus rotundifolia*, whereas the abundant pine forests of the region would result from recent afforestations.¹⁵ A further assumption is the competitive superiority of *Quercus* relative to *Pinus* under 'stable' conditions. The data presented here, however, fail to show evidence of any original *Quercus* forest, nor the expected replacement of *Pinus* by *Quercus* at the beginning of the Holocene, when current conditions developed. On the contrary, based on our palaeo-evidence, we conclude that over a long period of time, oaks may have competed with pines and lost. This could be a good example of what has been called 'home field advantage',¹⁶ which assumes that the species occupying a particular niche in a particular habitat will resist invasion even of highly fit taxa with comparable ecological requirements. Interestingly, it was not until an abiotically induced change occurred in the form of fire when oaks were able to colonize the area and formed a new type of forest. Moreover, some data suggest human interference at the same time as the first fire events, namely the installation of a Neolithic settlement near the study site and the synchronous introduction of agricultural practices and animal domestication.⁷ However, anthropogenic indicators in the pollen diagram such as *Plantago* occur slightly later (Fig. 1) and do not support this hypothesis. In conclusion, the floristic-phytosociological approach has traced a picture of vegetation dynamics and stable conditions that does not agree with our palynological data, which show that the role of *Pinus* as

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1. Andreae M.O., Fishman J. and Lindesay J. (1996). The Southern Tropical Atlantic Region Experiment (STARE): Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE A) and Southern African Fire-Atmosphere Research Initiative (SAFARI): an introduction. *J. Geophys. Res.* **101**, 23519–23520.
2. Van Wilgen B.W., Andreae M.O., Goldammer J.G. and Lindesay J.A. (eds) (1997). *Fire and the Southern African Savannas: Ecological and Atmospheric Perspectives*. Witwatersrand University Press, Johannesburg.
3. Fishman J., Reichle J.R. (1990). The significance of biomass burning as a source of carbon monoxide and ozone in the southern hemisphere tropics: a satellite analysis. *J. Geophys. Res.* **95**, 16443–16450.
4. Helas G., Andreae M.O., Schebeske G. and LeCanut P. (1995). SAARI-94: a preliminary view of results. *S. Afr. J. Sci.* **91**, 360–362.
5. Held G., Scheifinger H. and Snyman G.M. (1994). Recirculation of pollutants in the atmosphere of the South African highveld. *S. Afr. J. Sci.* **90**, 91–97.
6. Annegarn H.J., Braga Marcazzan G.M., Cereda E., Marchionni M. and Zucchiatti A. (1992). Source profiles by unique ratios (SPUR) analysis: determination of source profiles from receptor-site streaker samples. *Atmos. Environ.* **26A**, 2, 333–343.
7. Held G., Gore B.J., Surrridge A.D., Tosen G.R., Turner C.R. and Walmsley R.D. (1996). *Air Pollution and Its Impacts on the South African Highveld*. Environmental Scientific Association, Cleveland, Ohio.
8. Piketh S.J. (1995). Generation and transportation characteristics of suspended particles in the eastern Transvaal. M.Sc. thesis, University of the Witwatersrand.
9. Piketh S.J., Annegarn H.J. and Kneen M.A. (1995). Regional scale impacts of biomass burning emissions over southern Africa. In *Biomass Burning and Global Change*, ed. J.S. Levine, pp. 320–326. MIT Press, Cambridge.
10. Garstang M., Tyson P.D., Swap R.J., Edwards M., Källberg P. and Lindesay J.A. (1996). Horizontal and vertical transport of air over southern Africa. *J. Geophys. Res.* **101**, 23721–36.
11. Tyson P.D., Garstang M., Swap R.J., Edwards M. and Källberg P. (1996). An air transport climatology for subtropical southern Africa. *Int. J. Clim.* **16**, 265–91.
12. Garstang M. and Tyson P.D. (1997). Atmospheric circulation, vertical structure and transport. In *Fire and the Southern African Savannas: Ecological and Atmospheric Perspectives*, eds B. Van Wilgen, M.O. Andreae, J. Goldammer and J.A. Lindesay, pp. 57–88. Witwatersrand University Press, Johannesburg.
13. Charlson R.J., Langer J., Rodhe H. and Warren, S.G. (1991). Perturbation of the northern hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols. *Tellus* **43AB**, 152–163.
14. Swap R.J., Garstang M., Greco S., Talbot R.W. and Källberg P. (1992). Saharan dust in the Amazon Basin. *Tellus* **44B**, 133–149.
15. Scholes R.J. and Walker B.H. (1993). *An African Savanna: Synthesis of the Nytsolei Study*. Cambridge University Press, Cambridge.
16. Swap R.J., Garstang M., Macko S.A., Tyson P.D., Maenhaut W., Artaxo P. and Källberg P. (1996). The long-range transport of southern African aerosols to the tropical south Atlantic. *J. Geophys. Res.* **101**, 23777–23793.
17. Maenhaut W., Salma I., Cafmeyer J., Annegarn H.J. and Andreae, M.O. (1996). Regional atmospheric aerosol composition and sources in the eastern Transvaal, South Africa, and impacts of biomass burning. *J. Geophys. Res.* **101**, D19, 23631–23650.
18. Tyson P.D., Garstang M., Swap R.J., Browell E.V., Diab R.D. and Thompson A.M. (1996). Transport and vertical structure of ozone and aerosol distributions over southern Africa. In *Biomass Burning and Global Change*, ed. J.S. Levine, pp. 403–421. MIT Press, Cambridge.
19. Tyson P.D. (1997). Atmospheric transport of aerosols and trace gases over southern Africa. *Prog. Phys. Geog.* **21**, 79–101.
20. Cosijn C. and Tyson P.D. (1996). Stable discontinuities the atmosphere over South Africa. *S. Afr. J. Sci.* **92**, 381–386.
21. Talbot R.W., Harris R.C., Browell E.V., Gregory G.L., Sebacher D.I. and Beck S.M. (1986). Distribution of geochemistry of aerosols in the tropical North Atlantic troposphere: relationship to Saharan dust. *J. Geophys. Res.* **91**, 5173–5182.
22. Talbot R.W., Andreae M.O., Berresheim H., Artaxo P., Garstang M., Harris R.C., Beecher K.M. and Li S.M. (1990). Aerosol chemistry during the wet seasons in central Amazonia: the influence of long-range transport. *J. Geophys. Res.* **93**, 16955–16969.
23. Cachier H., Liousse C., Pertuisot M., Gaudichet A., Echalar F. and Lacaux J. (1996). African fire particulate emissions and atmospheric influence. In *Biomass Burning and Global Change*, ed. J.S. Levine, pp. 428–440. MIT Press, Cambridge.
24. Macko S.A., Estep M.L.F., Hare P.E. and Hoering T.C. (1987). Isotopic fractionation of nitrogen and carbon in the synthesis of amino acids by microorganisms. *Isotop. Geosci.* **15**, 333–352.
25. Rundel P.W., Ehleringer J.R. and Nagy K.A. (1989). *Stable Isotopes in Ecological Research*. Springer-Verlag, New York.
26. Warneck P. (1988). *Chemistry of the Natural Atmosphere*. International Geophysics Series, 41, Academic Press, London.
27. Atkinson R., Aschmann S.M., Carter W.P.L., Winer A.M. and Pitts J.N. (1982). Alkyl nitrate formation from NO_x-air photo-oxidation of C₂-C₄ n-alkanes. *J. Phys. Chem.* **86**, 4563–4569.
28. Atlas E., Pollock W., Greenberg J. and Heidt L. (1993). Alkyl nitrates, nonmethane hydrocarbons, and halocarbon gases over the equatorial Pacific Ocean during Saga 3. *J. Geophys. Res.* **98**(D9), 16933–16947.
29. Flocke F., Voltz-Thomas A. and Kley D. (1991). Measurements of alkyl nitrates in rural and polluted air masses. *Atmos. Environ.* **25A**, 1951–1960.
30. Shepson P.B., Anlauf K.G., Bottenheim J.W., Wiebe H.A., Gao N., Muthuramu K. and MacKay G.I. (1993). Alkyl nitrates and their contribution to reactive nitrogen at a rural site in Ontario. *Atmos. Environ.* **27A**, 749–757.
31. Luxenhofer O., Schneider E. and Ballschmiter K. (1994). Separation, detection and occurrence of (C₂-C₄)-alkyl- and phenyl-alkyl nitrates as trace compounds in clean and polluted air. *J. Chem.* **350**, 384–394.
32. Atlas E. and Schaufli S. (1991). Analysis of alkyl nitrates and selected halocarbons in the ambient atmosphere using a charcoal pre-concentration technique. *Environ. Sci. Technol.* **25**, 61–67.
33. Atlas E., Schaufli S.M., Merrill J.T., Hahn C.J., Ridley B., Walega J., Greenberg J., Heidt L. and Zimmerman P. (1992). Alkyl nitrate and selected halocarbon measurements at Mauna Loa Observatory, Hawaii. *J. Geophys. Res.* **97**(D10), 10331–10348.
34. De Kock, A.C. and Anderson C.R. (1994). The measurement of C₂-C₄ alkyl nitrates at a coastal sampling site in the southern hemisphere. *Chemosphere* **29**, 299–310.
35. Wiedmann T.O., Günther B., Class T.J. and Ballschmiter K. (1994). Global distribution of tetrachloroethene in the troposphere: measurements and modelling. *Environ. Sci. Technol.* **28**, 2321–2329.
36. Koppmann R., Johnen E.J., Plass-Dülmer C. and Rudolph J. (1993). Distribution of methylchloride, trichloroethene, and tetrachloroethene over the North and South Atlantic. *J. Geophys. Res.* **98**(D11), 20517–20526.
37. Class T.H. and Ballschmiter K. (1988). Chemistry of organic traces in the air VIII: sources and distribution of bromo- and bromochloromethanes in marine air and surface water of the Atlantic Ocean. *J. Atmos. Chem.* **6**, 35–46.
38. Labuschagne C. (1995). The distribution of halogenated hydrocarbons in a coastal environment. M.Sc. thesis, University of Port Elizabeth.
39. Freiman M.T., D'Abreton P.C. and Piketh S.J. (1998). Regional airflow over the southern Drakensberg Mountains of South Africa. *S. Afr. J. Sci.* **94**, 561–566.

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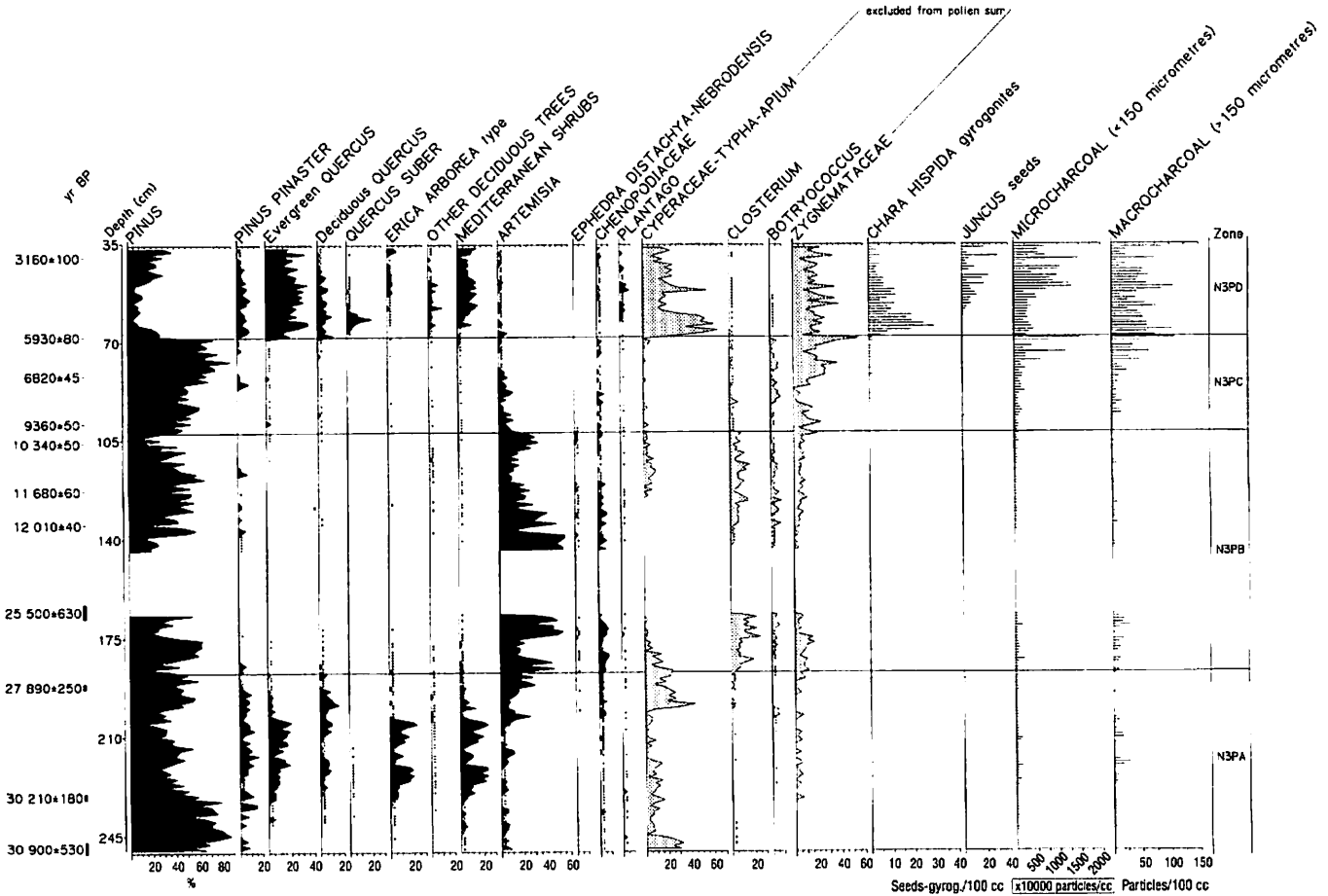


Fig. 1. Palaeoecological sequence of Navarrés peatbog, Valencia, eastern Spain. Relative abundances of the more important pollen, spore and seed taxa together with charcoal concentrations are plotted with respect to depth.

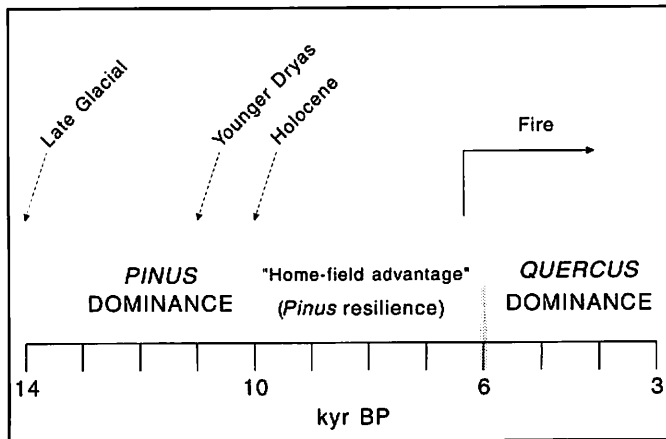


Fig. 2. The Navarrés history. A pine forest, which represents the glacial vegetation, persists unaltered despite Late Glacial, Younger Dryas and Holocene climatic changes, until abruptly removed around 6000 BP owing to fire events. The new ecological structure is dominated by *Quercus*, which, according to floristic-phytosociological assumptions, should have replaced *Pinus* at the outset of the Holocene.

a natural component of the Iberian forests has clearly been underestimated.

This sequence also confirms that we should be much more cautious when inferring climate models from pollen data. The pollen curve of *Artemisia* and, for a great part of the sequence, also the curve of *Pinus*, may represent a good palaeoclimatic signal, but the vegetation history of Navarrés does not seem to

be systematically and primarily caused by climatic factors. On the other hand, the causes of the two major vegetation changes are far from clearly understood. While the *Quercus* development during N3PA could be successional or climatically influenced, a similar tendency during N3PD may well have been a response to catastrophic fires through the intervention of man or a consequence of random processes of colonization. Navarrés is a unique sequence with its own idiosyncrasies. Trends surely exist, but the vegetation changes appear to be contextual rather than absolute. It seems that every event is due to the interaction of different factors with different impacts and for each the history should be determined individually. This may not be a popular history as it does not conform with existing concepts, but from a scientific point of view it should be acceptable to traditional ecologists.

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1. Westhoff V. and Van der Maarel E. (1973). The Braun-Blanquet approach. In *Ordination and Classification of Communities*. ed R.H. Whittaker, pp. 617-726. Dr W. Junk, The Hague.
2. Peinado M., Alcaraz F. and Martínez-Parras J.M. (1992). *Vegetation of Southeastern Spain*. J. Cramer, Berlin.
3. Mucina L. (1997). Classification of vegetation: past, present and future. *J. Veget. Sci.* 8, 751-760.
4. Brown L.R., Bredenkamp G.J. and Van Rooyen N. (1997). Phytosociological synthesis of the vegetation of the Borakalalo Nature Reserve, North-West Province. *S. Afr. J. Bot.* 63, 242-253.
5. Peinado M., Aguirre J.L. and Delgadillo J. (1997). Phytosociological, bioclimatic and biogeographical classification of woody climax communities of western

- North America. *J. Veget. Sci.* 8, 505–528.
6. Rivas-Martínez S. (1997). Syntaxonomical synopsis of the potential natural plant communities of North America, 1. *Itinera geobotanica* 10, 5–148.
 7. Carrión J.S. and Van Geel B. (submitted). Fine resolution palaeoecological record from the Late Pleistocene and Holocene site of Navarrés (Valencia, Mediterranean Spain). *Rev. Palaeobot. Palynol.*
 8. Willis K. (1996). Where did all the flowers go? The fate of temperate European flora during glacial periods. *Endeavour* 20, 110–114.
 9. Magri D. and Parra I. (1997). Rifugi mediterranei di vegetazione arborea nel Tardo-Quaternario. In *Atti del 4 Colloquio su Approcci metodologici per la definizione dell ambiente fisico e biologico mediterraneo*, pp. 1–17. Edizioni Orantes.
 10. Carrión J.S., Munuera M. and Navarro C. (1998). The palaeoenvironment of Carhuela Cave (Granada, Spain). A reconstruction on the basis of palynological investigations of cave sediments. *Rev. Palaeobot. Palynol.* 99, 117–144.
 11. Watts W.A., Allen J.R.M., Huntley B. and Fritz S.C. (1996). Vegetation history and climate of the last 15,000 years at Laghi di Monticchio, southern Italy. *Quat. Sci. Rev.* 15, 133–153.
 12. Willis K.J. (1994). The vegetational history of the Balkans. *Quat. Sci. Rev.* 13, 769–788.
 13. Pausas J.G. (1997). Resprouting of *Quercus suber* in NE Spain after fire. *J. Veget. Sci.* 8, 703–706.
 14. Carrión J.S. and Dupré M. (1996). Late Quaternary vegetational history at Navarrés, eastern Spain. A two core approach. *New Phytol.* 134, 177–191.
 15. Costa M. (1987). El País Valenciano. In *La Vegetación de España*, eds M. Peinado and S. Rivas-Martínez, pp. 281–308. Universidad de Alcalá de Henares, Madrid.
 16. Pimm S.L. (1991). *The Balance of Nature?* University of Chicago Press, Chicago.

A 3000-year isotopic record from a stalagmite in Cold Air Cave, Makapansgat Valley, Northern Province

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Detailed, high-resolution palaeoclimatic records are essential for understanding process and variability of late Holocene climate change, yet suitable proxies for the largely arid southern African region are rare. Under certain conditions, cave speleothems can provide high-resolution records that sensitively reflect local climate variables and provide clues to the regional response of larger-scale climatic features. Here we report $^{18}\text{O}/^{16}\text{O}$ and $^{13}\text{C}/^{12}\text{C}$ ratios from a well-dated, continuous, aragonitic stalagmite from Cold Air Cave in the Makapansgat Valley, Northern Province, South Africa. Carbon and oxygen isotope records are broadly in phase although amplitude of carbon isotope shifts is not large by carbon isotope standards. The data suggest that C_4 grasses were more abundant in wetter, warmer conditions and somewhat suppressed in drier, cooler conditions. Amplitude of oxygen isotope shifts is high and suggests a positive relationship with temperature, unlike the Cango Cave stalagmite. An extended period of oxygen isotope depletion, beginning at about AD 1400 and culminating in a marked depression at about AD 1700, is interpreted as the regional manifestation of the Little Ice Age.

Speleothems are extremely useful in palaeoclimate studies because growth is continuous (or semi-continuous) and characterized by incremental growth bands, and isotopic ratios in these increments reflect ambient conditions. Hence they can encode both long-term and high-resolution data about climate variability, temperatures, and the nature of the overlying vegetation.

Use of isotopic ratios from speleothems in palaeoclimate studies is based mainly on the temperature dependence of $^{18}\text{O}/^{16}\text{O}$ fractionation during crystallization of the carbonate, while the strong influence of plant-derived CO_2 on $^{13}\text{C}/^{12}\text{C}$ reflects photosynthetic pathways (C_3 and C_4) in overlying vege-

tation.¹ Small components of the $^{13}\text{C}/^{12}\text{C}$ signal are also derived from atmospheric CO_2 and bedrock carbonate, which may dampen the plant signal slightly.^{1,2} An essential requirement is that conditions of isotopic equilibrium must pertain during formation of the calcium carbonate from its parent water. Carbonate $^{18}\text{O}/^{16}\text{O}$ depends both on isotopic composition of the water (expressed in the notation as $\delta^{18}\text{O}_w$ ($\delta^{18}\text{O} (‰) = (R_s/R_{ref} - 1) \times 1000$, where $R = ^{18}\text{O}/^{16}\text{O}$) from which it is precipitated and temperature (T). These variables are expressed in Craig's³ palaeotemperature Equation (1) that relates the isotopic composition of calcite (expressed as $\delta^{18}\text{O}_c$) to the mean annual ambient temperature.

$$T^\circ\text{C} = 16.9 - 4.2 (\delta^{18}\text{O}_c - \delta^{18}\text{O}_w) + 0.13(\delta^{18}\text{O}_c - \delta^{18}\text{O}_w)^2 \quad (1)$$

This equation changes slightly when using the metastable mineral type, aragonite.⁴ But $\delta^{18}\text{O}_w$ is also independently T-dependent, and negative or positive relationships between $\delta^{18}\text{O}_c$ and T are possible, due to coupled or opposed T-dependencies of the calcite–water fractionation (which is always negative) and $\delta^{18}\text{O}_w$ in rainfall.⁵ The determination of both $\delta^{18}\text{O}_w$ and the relative importance of $\delta^{18}\text{O}_w$ and T, represents one of the major constraints for deriving palaeoclimate information from speleothems.

Following the pioneering work of Hendy,⁶ stalagmite studies have been reported worldwide, many of which document glacial-interglacial changes.^{5–7} Fewer studies exist for semi-arid regions, but a comprehensive speleothem-based study has documented rainfall and vegetation change over the last ~20 000 years in the eastern Mediterranean region.^{7,8} Although a few isotopic values for speleothems in the Northern Province have been reported⁹, to date, the only systematic study exploiting these principles in South Africa was that of a stalagmite from Cango Cave² in the Southern Cape. A palaeotemperature record for much of the last 30 000 years was obtained from a series of $\delta^{18}\text{O}_c$ determinations along the growth axis of the 2.6-m-tall stalagmite by substituting $\delta^{18}\text{O}_w$ values obtained from the Uitenhage aquifer at appropriate ages, into Equation (1). This record probably represents the single most important, semi-continuous, quantitative temperature record in the South African Quaternary. One other semi-continuous record was obtained from a stalagmite in Lobatse II Cave, Botswana, which revealed climate fluctuations at intervals between 21 000 and 50 000 years ago.¹⁰

High-resolution records documenting climate conditions during the last few thousand years have been identified as high priorities in palaeoclimate research. No high-resolution studies of stalagmites have yet been reported in southern Africa. Here we report the first set of isotopic results for such a study, based on high-resolution sampling of the upper half of a stalagmite called 'T7', Cold Air Cave, 24°08.786'S 29°10.175'E, in the

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