A 160,000-Year Record of Dune Development and Atmospheric Circulation in Southern Arabia

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Aeolian deposits in the Wahiba Sands, Sultanate of Oman, reveal patterns of atmospheric circulation over the past 160,000 years. Luminescence dating indicates a correlation of dune activity with periods of low global sea level and decreased monsoon intensity. Evidence from dune orientation and sedimentary structures shows exclusively northbound transport of sand during times of high-latitude glaciation. These results are in contrast to the current paleocirculation model that assumes an increase of northwesterly winds because of a southward shift of the Intertropical Convergence Zone. Our results indicate that the circulation pattern during glacial times was comparable to that of the present.

The Indian Ocean monsoon is one of Earth's major weather systems. Southern Arabia is affected by the western margin of monsoon circulation, which controls the wind field and the amount of precipitation acting on the terrestrial environments. At present, atmospheric circulation in summer is dominated by a series of low-pressure cells that are located along the Intertropical Convergence Zone (ITCZ) north of the Wahiba Sands (Fig. 1, A and B) and all across southern Arabia (Fig. 2A). During winter, the ITCZ is forced to a position just south of the equator, while a persistent high-pressure cell with very low wind intensities exists over northern Oman (Fig. 2B) (*1*). Winds acting on the Wahiba Sands during summer are predominantly derived from southwesterly monsoon circulation deflected by the low-pressure trough along the ITCZ (Fig. 2A). The study area is not affected by monsoon-induced precipitation, which reaches as far north as the Dhofar region in southernmost Oman. The climate in southern Arabia is generally hyperarid, and precipitation in the Wahiba Sands is ~100 mm per year (*2*).

Evidence of past changes in monsoon dynamics comes from sedimentary archives of the dust and pollen input into the Arabian Sea and the upwelling intensity induced by summer and winter monsoons (*3–5*). Intensified monsoon circulation causing significantly higher precipitation over the Arabian Peninsula during the Holocene climatic optimum [5.5 to 9.5 thousand years ago (ka)] was identified in marine sediment cores and in terrestrial geoarchives of southern Arabia (*4*, *6–12*). Earlier pluvial phases occurred during marine isotope stages (MISs) 5a, 5e, 7, and 9 (*6*, *7*), indicating a complex change in circulation during these periods. Throughout these times, the position of the ITCZ was probably much further to the north. An increase of dust input into the Arabian Sea during times of high-latitude glaciations has been recognized in deep-sea sediment cores (*13*). Major source areas of this dust flux were the then–dried-out Persian Gulf and the Rub' al Khali. From this evidence it was deduced that the present dominant southern circulation over the Arabian Sea was substituted or at least strongly influenced by an increase of northwesterly winds (*14*). Despite their importance for the understanding of the overall monsoon dynamics, these proxies do not, however, allow a direct reconstruction of low-level wind dynamics. Fortunately, the orientation of dunes and the internal sedimentary structures of aeolian deposits formed during dune migration indicate the prevailing regional wind direction, and a chronological framework for periods of aeolian activity can be elaborated by luminescence dating (*15*).

The Wahiba Sands cover an area of approximately 10,000 km^2 extending 100 to 200 km from the present coastline to the margin of the Oman Mountains (Fig. 1B). The thickness of the aeolian succession reaches up to 150 m in the northern parts of the accumulation (fig. S1). Its formation has been assigned to times of low global sea level because of the presence of high amounts of allochemical fragments within the aeolian deposits (*16*). It was correlated with the period of last maximum high-latitude glaciation (Late Weichselian/Wisconsinan) based on a few luminescence dating results (*17*, *18*). This study provides the chronostratigraphic framework of aeolian dune formation in the Wahiba Sands based on 74 luminescence ages (table S1). Samples for luminescence dating were collected from outcrops of aeolian sandstones at the western Plateau of Al Jabin and from two sediment cores (WDR-1 and WDR-2) that were drilled within the High Sands of the northern Wahiba Sands (*19*) (Fig. 1B and fig. S1).

At Al Jabin, carbonate-cemented aeolian sandstones are intercalated with six soil horizons, representing intervals of either increased bioturbation or calcrete formation. These horizons are assigned to periods of slightly increased precipitation sufficient to sustain a minimal vegetation cover and bioactivity. Dune formation interrupted by pluvial events in this part of the desert took place between about 140 and 160 ka, as indicated by the dating results. This interval is correlated with MIS 6 and thus with the final part of the penultimate glacial cycle (Saalian/Illinoian). The pluvial events were of weak and/or regional character, because none of these humid spells have been identified in the speleothem records of Oman (*6*, *7*). There is no dating evidence of substantial breaks within this part of the aeolian sequence. The duration of these phases of increased wetness is thus likely to have been of millennial or centennial scale.

Small hills representing erosional remnants of lithified paleodunes and patchy veneers of

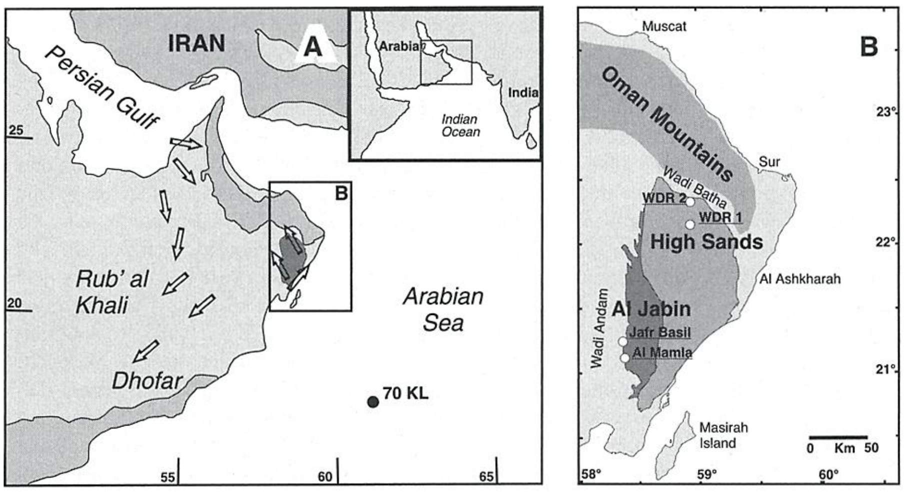

Fig. 1. Maps showing the location of the Wahiba Sands and the direction of dune movement in SE Arabia (*17*, *24*) (**A**) and the position of relevant sites mentioned in the text (**B**). The gray scale in (A) moves from light to dark as follows: white (ocean), light gray (continent), medium gray (terrain above 300 m above sea level), and dark gray (Wahiba Sands).

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fluvial gravel on the Al Jabin Plateau result from subsequent extensive erosion by southerly directed ephemeral streams originating from the Oman Mountains (*16*, *20*). Fluvial deposits of similar origin at the basal part of core WDR-1 (core meters 91 to 144 m) have been dated as being older than 100,000 years (table S1). This period of fluvial activity is correlated with a significant increase in annual precipitation during the last interglacial (MIS 5e) observed in the speleothem record (*6*, *7*). Dune sands overlying a well-developed calcrete at Jafr Basil, as well as the aeolian sandstones above the fluvial sequence of core WDR-1 and from the basal part of WDR-2, are dated about 100,000 to 120,000 years old. This phase of aeolian sedimentation is thus assigned to MIS 5d. In core WDR-1, the aeolian deposits are intercalated with three calcrete horizons, which represent pluvial events interrupting dune formation similar to those that occurred during MIS 6. More recent main periods of sand accumulation took place around 64 to 78 ka (MIS 4) and 18 to 22 ka [MIS 2, Last Glacial Maximum (LGM)]. All these intervals corresponded to lower global sea levels, glaciations at high latitude (*21*), and times of low monsoon intensity (*22*). We concluded that Pleistocene dune activity reflects phases of increased sediment availability from the then–partly exposed continental shelf, decreased precipitation, and resulting reduced vegetation cover. Increased aeolian activity is also recorded well by periods of maximum dust input in Oman Sea sediment core 70KL (*23*) (Fig. 3). During the Holocene, dune formation by the remobilization of Pleistocene paleodunes took place around 2 ka and 700 years ago (fig. S1 and table S1).

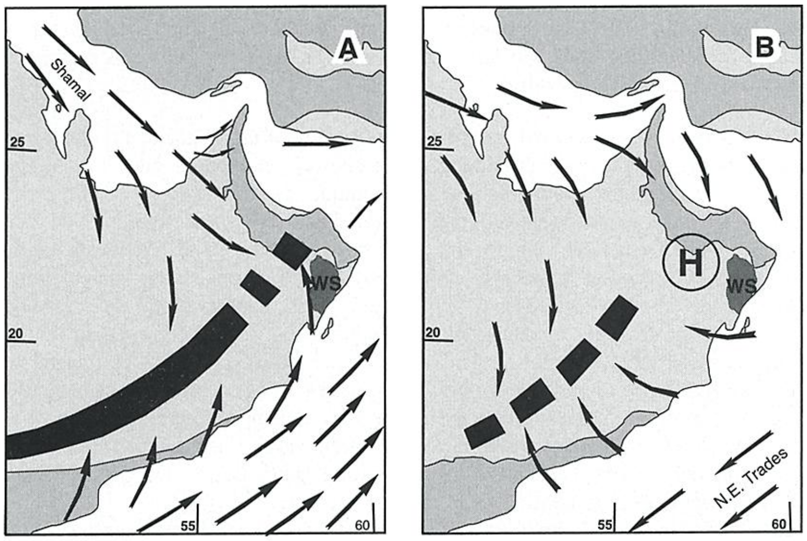

Fig. 2. The present low-level circulation pattern during summer (**A**) and winter (**B**) (*27*), where the position of the ITCZ is marked by the thick black line. WS marks the position of the Wahiba Sands. The dashed line in (B) represents a temporally occurring local convergence, and H marks the approximate position of the high-pressure cell (*28*).

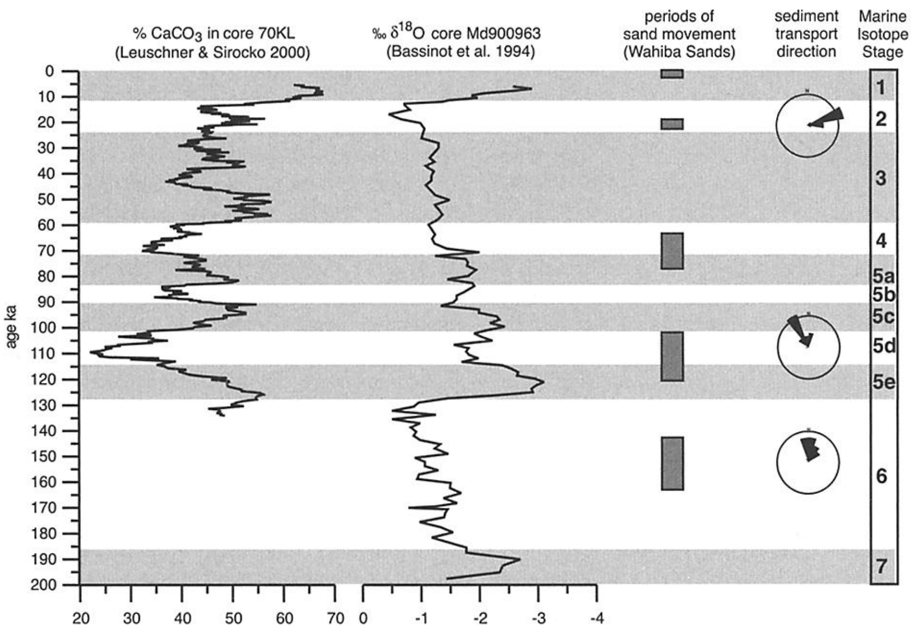

Fig. 3. Comparison of the $CaCO_3$ content in core 70KL (an inverse measure of dust input) (*23*), and the oxygen isotope record from core Md900963 from the Maldives area (*21*) with the timing of aeolian activity in the Wahiba Sands. The individual duration of the periods of dune movement was calculated from the standard deviation of the weighted mean luminescence age. Rose-diagrams show the distribution of sand transport vectors in the Wahiba Sands from outcrop studies.

For the reconstruction of paleocirculation, it is important to recognize that during glacial periods, the sedimentary structures within the aeolian deposits of the Wahiba Sands indicate that sand was transported exclusively by southerly winds (Fig. 3). The alignment of dune ridges also follows the present summer circulation pattern caused by the persistent low-pressure belt present over central Oman (Figs. 1A and 2A) (*24*). Dunes in the United Arab Emirates (UAE), north of the present ITCZ, were formed by the influence of northwesterly winds (*18*, *24*). The periods of aeolian activity recognized in the UAE were synchronous to those in the Wahiba Sands (*18*). This result implies that the wind regime causing the formation of the Pleistocene dunes in Southern Arabia was similar to the present-day circulation pattern. There is no evidence of any impact of northwesterly winds on dune formation in the Wahiba Sands as would be expected according to the current paleocirculation model for times of high-latitude glaciations (*14*). Furthermore, isotopic signatures of Late Pleistocene groundwater in northern Oman also indicate a southerly, Indian Ocean source of precipitation during the LGM (*25*). In addition, upwelling on the Arabian Shelf has been reported for the time of the LGM (*5*).

The increased transport of dust from the Persian Gulf area into the Arabian Sea during times of high-latitude glaciation can be explained with the following scenario: During glacial times, the then–dried-out Persian Gulf became an important source of fine material (*26*). Under the proposed circulation pattern (Fig. 2A), dust is lifted up in the Persian Gulf area and the northwestern Rub' al Khali to be transported a few thousand kilometers in the higher layers of the troposphere. The transport mode for dust seems to be a layer influenced by the NW-SE–oriented jet stream in the higher troposphere either above the near-surface high-pressure cell over northern Oman during winter or over the monsoon inversion during summer (*1*).

Our findings show that oceanic proxies may suggest a gross modal change in circulation that is not expressed in the terrestrial environment. This conclusion is important when interpreting past changes in moisture availability and sources of precipitation, such as the impact on monsoon circulation caused by shifting the position of the ITCZ to a more northerly or southerly position (*14*).

References and Notes

1. G. R. Iyengar, K. J. Ramesh, R. K. Paliwal, O. P. Madan, *Curr. Sci.* **80**, 18 (2001).
2. J. R. Jones, H. Weier, P. R. Considine, *J. Oman Stud. Spec. Rep.* **3**, 61 (1988).
3. R. R. Nair *et al.*, *Nature* **338**, 749 (1989).
4. E. Van Campo, J. C. Duplessy, M. Rossignol-Strick, *Nature* **296**, 56 (1982).
5. P. D. Naidu, B. A. Malmgren, *Paleoceanography* **11**, 129 (1996).
6. S. J. Burns, A. Matter, N. Frank, A. Mangini, *Geology* **26**, 499 (1998).
7. S. J. Burns, D. Fleitmann, A. Matter, U. Neff, A. Mangini, *Geology* **29**, 623 (2001).
8. I. D. Clark, J.-C. Fontes, *Quat. Res.* **33**, 320 (1990).
9. S. C. Clemens, W. Prell, D. Murray, G. Shimmield, G. Weedon, *Nature* **353**, 720 (1991).
10. J. Overpeck, D. Anderson, S. Trumbore, W. Prell, *Clim. Dyn.* **12**, 213 (1996).
11. A.-M. Lézine, J.-F. Saliège, C. Robert, F. Wertz, M.-L. Inizan, *Quat. Res.* **50**, 290 (1998).
12. H. A. McClure, *Nature* **263**, 755 (1976).
13. F. Sirocko, M. Sarnthein, in *NATO ASI Services C* 282, M. Leinen, M. Sarnhein, Eds. (Kluwer, Dordrecht, Netherlands, 1989), pp. 401–433.
14. F. Sirocko, M. Sarnthein, H. Lange, H. Erlenkeuser, *Quat. Res.* **36**, 72 (1991).
15. S. Stokes, D. S. G. Thomas, R. Washington, *Nature* **388**, 154 (1997).
16. R. A. M. Gardner, *J. Oman Stud. Spec. Rep.* **3**, 75 (1988).
17. K. W. Glennie, in *Quaternary Deserts and Climate Change*, A. Alsharhan, K. W. Glennie, G. L. Whittle, C. G. Kendall, Eds. (Balkema, Rotterdam, Netherlands, 1998), pp. 279–291.
18. N. Juyal, A. K. Singhvi, K. W. Glennie, in *Quaternary Deserts and Climate Change*, A. Alsharhan, K. W. Glennie, G. L. Whittle, C. G. Kendall, Eds. (Balkema, Rotterdam, Netherlands, 1998), pp. 315–325.
19. Supplementary figures; details of drilling, sampling, and experimental procedures; and the luminescence data set are available on *Science* Online.
20. J. Maizels, *J. Oman Stud. Spec. Rep.* **3**, 95 (1988).
21. F. C. Bassinot *et al.*, *Earth Planet. Sci. Lett.* **126**, 91 (1994).
22. M. Rossigniol-Strick, *Nature* **304**, 46 (1983).
23. D. C. Leuschner, F. Sirocko, *Quat. Sci. Rev.* **19**, 243 (2000).
24. C. Breed *et al.*, *USGS Prof. Pap.* **1052**, 305 (1980).
25. C. E. Weyhenmeyer *et al.*, *Science* **287**, 842 (2000).
26. E. Uchupi, S. A. Swift, D. A. Ross, *Mar. Geol.* **160**, 1 (1999).
27. G. Stanger, thesis, The Open University, Milton Keynes, UK, (1986).
28. D. E. Pedgely, *Meteorol. Mag.* **99**, 29 (1970).

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Supporting Online Material
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Materials and Methods
Figs. S1 and S2
Table S1

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Rapid Bottom Melting Widespread near Antarctic Ice Sheet Grounding Lines

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As continental ice from Antarctica reaches the grounding line and begins to float, its underside melts into the ocean. Results obtained with satellite radar interferometry reveal that bottom melt rates experienced by large outlet glaciers near their grounding lines are far higher than generally assumed. The melting rate is positively correlated with thermal forcing, increasing by 1 meter per year for each 0.1°C rise in ocean temperature. Where deep water has direct access to grounding lines, glaciers and ice shelves are vulnerable to ongoing increases in ocean temperature.

The undersides of ice streams flowing from the Antarctic continent typically melt into the ocean where they cross the grounding line and begin to float as ice shelves and ice tongues (*1*). Unlike melting under the grounded ice sheet, processes beneath floating glaciers are governed by the transport of ocean heat and by the seawater freezing temperature dependence on pressure (*2*). This allows sensible heat to be obtained from the cold, dense shelf waters resulting from sea ice formation, as well as "warm" deep water that intrudes onto the continental shelf and flows into ice shelf cavities. Bottom melting freshens and cools the seawater, adding buoyancy that drives upwelling as the ice shoals seaward. In some regions, the rising seawater-meltwater mixture drops below the in situ freezing point to form "marine" ice that can comprise a substantial part of ice shelf volume (*3, 4*). Where the continental shelf is broad and the inflows are cold and dense, some of the meltwater-laden outflows eventually sink and contribute to the formation of bottom water, which ventilates the deepest parts of the world's oceans (*5*). Net basal melting beneath the 1.6×10^6 km^2 floating portion of the Antarctic Ice Sheet (*6*), adjusted for recent lower estimates for the larger ice shelves (*4, 7*), is believed to be around 40 cm/year. But much of the actual melting occurs in the deepest parts of the sub–ice shelf cavities, where direct measurements are unavailable and would be very difficult to acquire.

Here we calculate basal melt rates at 23 of these remote interior regions, using satellite radar interferometry observations of grounding line position, ice velocity, and surface topography of outlet glaciers that nourish the ice shelves and ice tongues (*8*). With this technique, grounding lines can be precisely located and are often found to lie tens of kilometers landward of previously estimated positions (*9*). Basal melting calculations assume mass conservation and steady-state conditions between the grounding line and a flux gate located about one glacier-width downstream (*10*). Thickness changes due to short-term changes in creep rate, snow accumulation, and surface ablation are believed to be small compared with the large bottom melt rates obtained.

We focus on melt rates near the grounding lines of deep-draft outlet glaciers because continental ice discharge is principally controlled by the channeled flow of these ice streams into the ocean (Fig. 1). If these regions are the locus of high basal melting, the potential exists for substantial ocean control over ice shelf, if not ice sheet, mass balance (*11–13*). Indirect observations and computer models have suggested high basal melting in the proximity of deep grounding lines and have shown that melting efficiency will decrease as buoyant plumes lose heat and rise to shallower depths along ice-ocean interfaces (*14, 15*). Therefore, it is not the average ice shelf melt rate but the melt rate near the grounding line that will have the greatest impact on ice flow dynamics. As the properties and circulation of the ocean are modified by climate change, a corresponding change in the rate of basal melting in this region may alter ice thickness, move grounding lines, and accelerate the flow of ice into the sea.

The basal melt rates for the 23 glaciers shown in Fig. 1 are listed in Table 1. The spectrum of values ranges from <4 m/year for several glaciers that flow into the Filchner-Ronne Ice Shelves to >40 m/year for Pine Island Glacier. The wide range is consistent with earlier studies of several of the individual glaciers, using a variety of methods (*16–21*), and stems from quite different grounding line drafts, seawater temperatures,

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