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15. POLLEN TRANSPORT INTO ARABIAN SEA SEDIMENTS[1]

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INTRODUCTION

Pollen data from marine cores can provide continuous records of continental climatic events reflected by the vegetation history. Previous marine pollen studies in the western Arabian Sea (Van Campo et al., 1982, Prell and Van Campo, 1986) have shown major changes in the intensity of monsoonal climate during the last climatic cycle. Here we determine the quantitative and qualitative character of the palynological content of ODP Leg 117 sediments, its relation with regional modern pollen rain and onshore vegetation and climate, and its potential to reconstruct monsoon history. Long-term changes in the regional climate are recorded in the Oman margin (Holes 723A and B) and Owen Ridge (Hole 721B) sediments. They are characterized by the existence of a humid tropical, probably less seasonally contrasted climate back to the Pliocene, and the development of a higher seasonality associated with the development of glacial stages as recorded in the oxygen isotope records during the last million years.

ENVIRONMENTAL SETTING

Surface atmospheric circulation over northwestern Indian Ocean is controlled by the monsoonal system with seasonal low level wind reversal, following the latitudinal migration of the Intertropical Convergence Zone (I.T.C.Z.). During winter, surface heating and low pressure center are situated in the southern hemisphere, and the northern monsoon flow prevails (Ramage, 1971). During summer, the southwestern monsoon flow blows from the high pressure cell south of the Equator to the low pressure cell developed over Tibet and interacts with the Equatorial Westerlies, inducing coastal upwelling in the western Indian Ocean. This maritime current is too shallow to create any convective activity, which explains the weakness of summer rainfall regionally. Moreover, the upwelling intensifies coastal subsidence and summer dryness. The northwesterly dry hot winds originating in the subtropical high pressure cells and flowing across inland Arabia are strongest during summer in response to the intense heat low over south Asia. The steep pressure gradient created between this trough and the semi-permanent high pressure cell over North Saudi Arabia enhances these currents associated with maximum dust haze season over western Arabian Sea (McDonald, 1938). The northwestern Arabian Sea is surrounded by East Africa, Arabia, and southern Iran. The vegetation of these borderlands is controlled by regional climates and can be ascribed to different plant-geographical regions, the Mediterrano-Irano-Turanian, the Saharo-Arabian and the Sudanian regions (Zohary, 1973).

Northeast Africa belongs to the dry tropical Sudanian region (Fig. 1). In Somalia, two rainfall maxima, one in March-May, and one in October-November reflect the annual migration of the I.T.C.Z. Ethiopian Highlands are much wetter, but heavy summer rainfall is here partly derived from the westerly African monsoonal air.

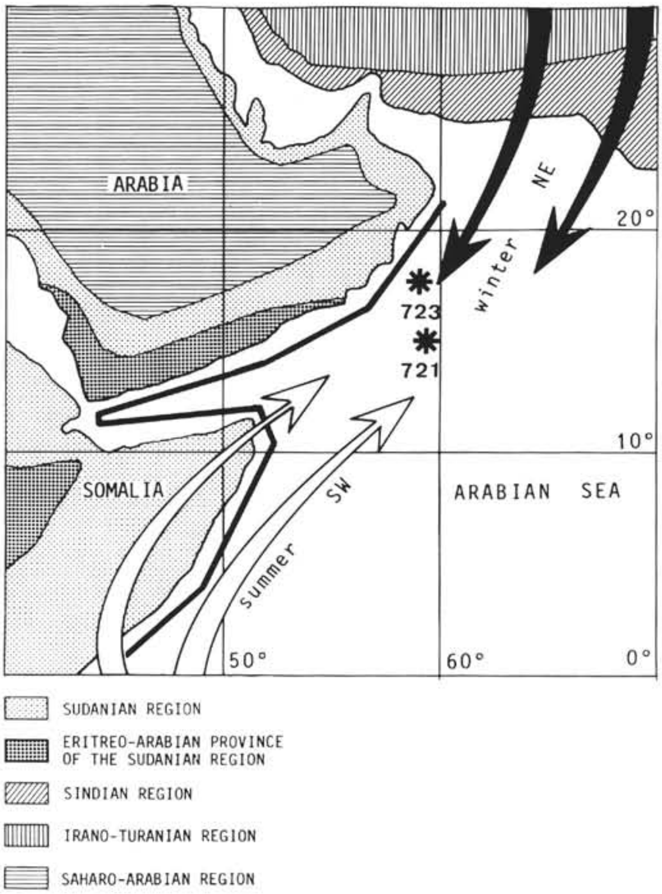

Figure 1. Major geographical-plants regions considered as pollen source areas, and location of Sites 721 and 723. Heavy line indicates ship routes with pollen collection on air filters. Arrows indicate the direction of seasonal wind flows.

Arabia can be divided into a tropical and an extratropical parts. The whole southern coast falls under the summer-rain climate, with some places enjoying a small amount of winter rains. The only areas receiving noteworthy monsoonal rainfall are the Yemen and Oman Highlands. The Sudanian region of tropical Arabia can be divided into an Eritreo-Arabian province, confined to the southern and southwestern parts, and a Nubo-Sindian province, which covers continuous areas or patches interrupted by deserts all along the more or less wide coastal belts of the peninsula up to south Iran. In the Eritreo-Arabian province, the vegetation is close of that of the mountainous East Africa, both in its flora and altitudinal zonation: Afro-Alpine grassland and Ericaceous shrub above 3000–3500 m, tropical montane

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forest with *Juniperus*, *Podocarpus*, and *Olea* at 2000–3000 m. Below, *Acacia* and *Commiphora* bushes occur. No sharp boundary can be given in the dry tropical formations including bush and savannah formations of middle altitude, and the pseudo-savannah and dwarf-shrub deserts of the lowlands. The north extratropical Arabia belongs to the Saharo-Arabian region. The climate is of the Mediterranean pattern with scant winter rains to almost no rain in central areas and hot and dry summers, with many variants of steppic and desertic vegetation types.

From inland south Iran to northwestern India, the Irano-Turanian region is characterized by a semi-continental climate with low precipitation and large annual temperature amplitude, and steppic vegetation.

In summary, except under particularly favorable conditions, most lands surrounding the Arabian Sea are occupied by steppes and deserts covered by a dwarf-shrub or herbaceous open vegetation. The pollen rain originating from these lands has been studied both spatially and seasonally, in order to establish its relationship to vegetation and to interpret the fossil pollen data.

MODERN ATMOSPHERE POLLEN CONTENT

The basis for interpreting past pollen spectra from marine sediments in western Arabian Sea is provided by studies of modern pollen spectra, considered with the source areas and ecology of common pollen producers and transport characteristics. Fluvial sediment influx from these arid lands to the sea is negligible, and eolian transport is dominant (Kolla et al., 1981). The climatic interpretation of the pollen record then relies on the seasonal and spatial distribution of the modern atmospheric pollen over the western Arabian Sea. Pollen are introduced in the marine atmosphere either by current pollen production at the flowering period, or by reworking of land surface grains. The mineral and organic particles in suspension in the air are carried away with the prevailing winds.

Pollen was collected with air filters on board ships travelling along the coasts of Africa and Arabia between 1981 and 1983. We selected two series of seasonally opposed transects, off the coast of Somalia and Arabia (Fig. 1). The characteristics of each transect are listed in Table 1. The samples available from the winter monsoon are mainly off south Arabia. Those from summer monsoon were collected off south Arabia and Somalia. Quantitative and qualitative pollen analysis were performed in order to study the seasonal variations in the marine atmosphere pollen content, between winter and summer monsoon periods. According to the atmospheric circulation over the western Arabian Sea and the dust transport patterns (Prospero et al. 1981; Sirocko and Sarnthein, 1989), we can assume that the major part of land-derived material is coming off the Arabian peninsula and northeastern Africa associated with summer circulation. However, winter pollen transects (November–January) still contain pollen grains, which shows that the northerly flow also carries pollen over the Arabian Sea, as confirmed by the wind directions reported in Table 1.

A preliminary study of seasonally contrasted samples has shown that in the modern atmospheric pollen spectra, the dominant pollen types are Gramineae, Chenopodiaceae, Cyperaceae, and *Artemisia* (Van Campo, 1983). The only taxa that reach at least 1% in each transect are Gramineae and Cyperaceae during the summer and Chenopodiaceae, *Artemisia*, and Gramineae during the winter.The sum of these four taxa frequencies represent always more than 50% of the spectrum. These wind-pollinated plants are the major component of the herbaceous cover of arid and subarid areas.

The Chenopodiaceae largest representation occurs in the winter period, as they begin to flower in fall, but they are also present in other seasons. It is one of the plant families most characteristic of the vegetation of deserts and semi-deserts, including salines. *Artemisia* is a very important component of the vegetal cover in Mediterranean and Irano-Turanian steppes. The period of maximum representation starts at the end of fall, at the beginning of the flowering period. *Artemisia* needs cool to cold winters. Gramineae are the most abundant component of pollen rain. They are well-represented in summer, as their maximum pollen emission occurs at that time, and much less represented in winter. Gramineae cannot be considered strictly as a climatic indicator but are mostly characteristic of savanna grasslands. Cyperaceae are abundantly represented off Somalia desert at the beginning of the summer monsoon and their summer representation rapidly decreases northward. Cyperaceae pollen are absent in winter samples. A palynological transect from North (35°N) to Equatorial (5°N) Africa, near the 0° meridian, has shown that maximum representation of Cyperaceae occurs at the Sahara-Sahel boundary, under tropical regime (Cour and Duzer, 1980).

Many other pollen taxa were identified besides the four dominant ones. In a previous study, a monsoon pollen index (MPI) was established, as the sum of pollen types present exclusively during the summer, plus other types originating from humid or montane tropical northeast Africa and southwest Arabia, for example mangrove pollen, spores of Pteridophytes, *Podocarpus*, Combretaceae, *Alchornea*, and others (Prell and Van Campo, 1986). The MPI is the most diagnostic of the summer monsoon, even if the part of the transport and source area contributions is difficult to determine.

In conclusion, the present-day eolian pollen survey shows (1) a group of four dominant taxa (Gramineae, Chenopodiaceae,

Table 1. Atmospheric pollen samples off Saudi Arabia and Somalia.

Collection months	Latitude start	Latitude end	Exposure time (hr)	Predominant wind direction	Number pollen m^2/day/10 km	% Dominant herbaceous pollen taxa			
						Gramineae	Chenopodiaceae	Cyperaceae	*Artemisia*
November	11°5N	16°4N	144	missing	770	6.5	59.2	0.0	24.9
November	12°3N	22°0N	108	missing	1100	6.8	2.6	0.0	85.1
November	20°0N	15°4N	49	NE: 75%; SW: 25%	16210	4.3	54.0	2.4	27.8
December	11°3N	09°3N	72	missing	640	15.1	20.9	1.0	20.9
January	12°3N	13°4N	24	NE: 100%	1680	10.0	30.1	0.0	16.2
January	13°4N	21°2N	72	NE: 100%	990	10.5	44.7	0.7	16.2
May	19°0N	12°0N	36	SW: 100%	2680	26.9	17.0	5.3	8.2
May	12°0N	04°0N	39	NE: 20%; SW: 80%	1160	22.5	17.0	10.1	2.5
May	00°0N	05°1N	52	missing	13960	23.6	0.6	66.9	0.0
May	05°1N	09°0N	47	missing	67470	17.1	6.1	63.0	0.0
May	09°0N	11°0N	23	missing	87840	33.9	11.7	40.0	0.0
June	20°0N	13°3N	49	missing	38210	77.7	5.8	4.5	0.1
June	12°2N	03°5N	61	missing	4350	71.9	3.8	7.6	0.0
July	17°0N	10°0N	48	missing	1390	54.5	6.4	10.9	0.1
August	13°0N	15°5N	48	missing	4100	40.3	14.9	6.2	0.8

Cyperaceae and *Artemisia*), which represents the regional herbaceous vegetation, and (2) a very diversified group of few represented taxa, among which seasonal patterns define a MPI related to the southwest monsoon.

POLLEN RECORDS FROM LEG 117

The variation of the eolian pollen component, considered as the major source of pollen sedimentation on the seafloor in the Western Arabian Sea is recorded in the cores.

Pollen Preparation Method

Sample preparation followed standard techniques. After weighing and drying, HF and HCl were used to eliminate the mineral fraction, and Luber reaction, Na-hexametaphosphate, and KOH to eliminate the organic fraction. The residues were screened, first on a 200 μm mesh, and second on a 10 μm mesh in an ultrasonic basin to eliminate the fine remaining mineral particles. A 50 μL fraction of the diluted residue was mounted on a glass slide and sealed.

PALYNOLOGICAL RESULTS

Samples from Sites 723 and 721 were investigated for preliminary pollen studies. Sample gaps were wide and irregular, with a average of 10 m for each hole.

Site 723 is situated on the Oman Margin (18°3.079′N, 57°86.561′E). Hole 723A reached a total depth of 432.3 mbsf, and 37 samples from the top to 384 mbsf were analyzed for pollen. Pollen concentration varied in number from 198 to 2301 per gram. Hole 723B reached a total depth of 429.0 mbsf and 32 samples from the top to 351 mbsf were analyzed for pollen. Pollen concentration varied from 339 to 2634 per gram (Table 2). Holes 723A and B provide two representations of the same trends, each with quite different sampling intervals. For this reason, we can be assured that these trends are real and not a matter of sample bias. Since the accumulation rate is about 180 m/m.y., the individual sampling interval in each hole is about 50 k.y. and combined they are closer to 25 k.y.

Site 721 is situated on the Owen Ridge (16°40.636′N, 59°51.879′E). Hole 721B reached a total depth of 424.2 mbsf, and 31 samples from the top to 308 mbsf were analyzed for pollen. Pollen concentration varied from 3 to 1400 per gram.

For preliminary studies, the minimum pollen count is 100 pollen and spores. Most spores are grouped and not further differentiated. Botanical identification of the pollen grains goes commonly to the genus level, rarely to the species level. Unknown pollen do not reach more than 5% of the total pollen sum. A total of 90 pollen types was identified in the three investigated holes. The full list is appended (see Appendix). Table 2 shows dominant pollen masses and MPI with their average frequency for each hole. The dominant types recovered are the same as those identified today in the atmosphere. This low resolution preliminary sampling is an obstacle in the establishment of a climatically meaningful palynostratigraphy, and only large long-term trends can be observed (Figs. 2, 3). The most obvious trend is the increase in the frequency of *Artemisia* recorded at Site 723 (from 10% to 40%) and confirmed at Site 721. This

Table 2. Dominant pollen types and MPI in the holes.

Core	Hole 721B	Hole 723A	Hole 723B
Number of pollen	3320	6792	6533
% Chenopodiaceae	40.1	43.1	44.8
% Gramineae	25.0	19.5	18.0
% Cyperaceae	13.9	4.1	4.5
% *Artemisia*	3.0	16.5	18.9
% MPI	3.1	1.8	1.8

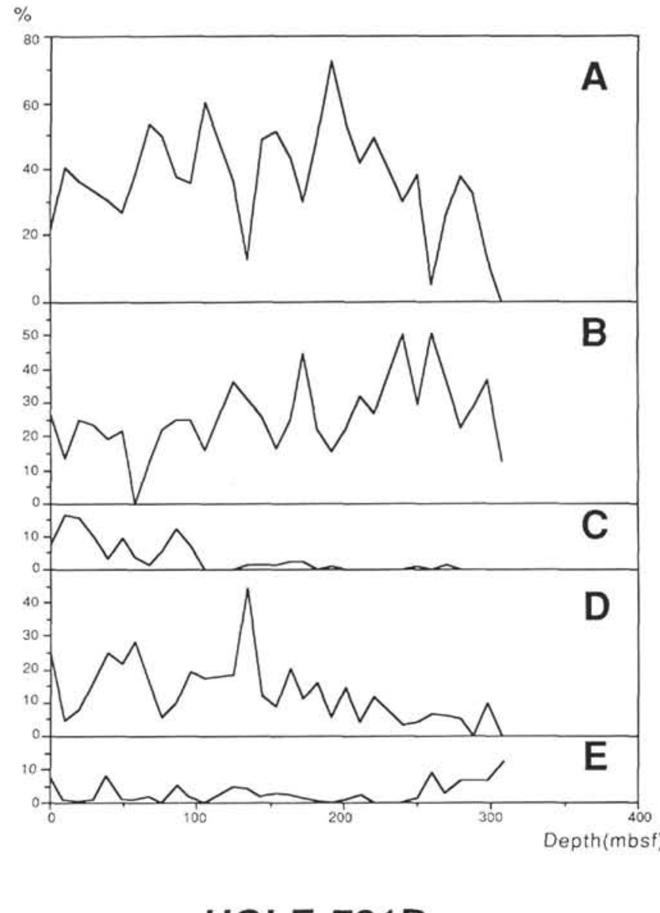

Figure 2. Percentages of dominant pollen types and Monsoon Pollen Index (MPI) in Holes 721B. **A.** Chenopodiaceae. **B.** Gramineae. **C.** *Artemisia*. **D.** Cyperaceae. **E.** MPI.

Mediterrano-Irano-Turanian pollen type increase is certainly related to polar cooling, rise of a higher seasonality and increase in circulation intensity. This trend is close to the time when glacial stages increase in the oxygen isotope record during the last million year in this region (see Niitsuma, this volume). The *Artemisia* data are also consistent with the increase in magnetic susceptibility data which could mean more eolian material deposited in the studied areas, in relation with the development of continental steppes and stronger meridional winds.

An MPI can be calculated from each hole and compared with marine indicators of the monsoon from the same holes. As the MPI includes most of the tropical pollen types, the presence of such types all through the records clearly shows the occurrence of a warm humid tropical climate, which was probably less seasonally contrasted in the Pliocene.

In both Sites 721 and 723, higher pollen abundances in the late Pliocene decrease toward the present. From these preliminary results, it is not possible to correlate this trend with the increase in *Artemisia* or with the variation of any pollen type.

CONCLUSIONS

These first results are very promising because they agree with the palynology of late Quaternary sediments and extend the use of the MPI and other pollen types, as recording the history of monsoon and regional climate of the borderings areas of Arabian Sea, back to the Neogene. A detailed investigation of the

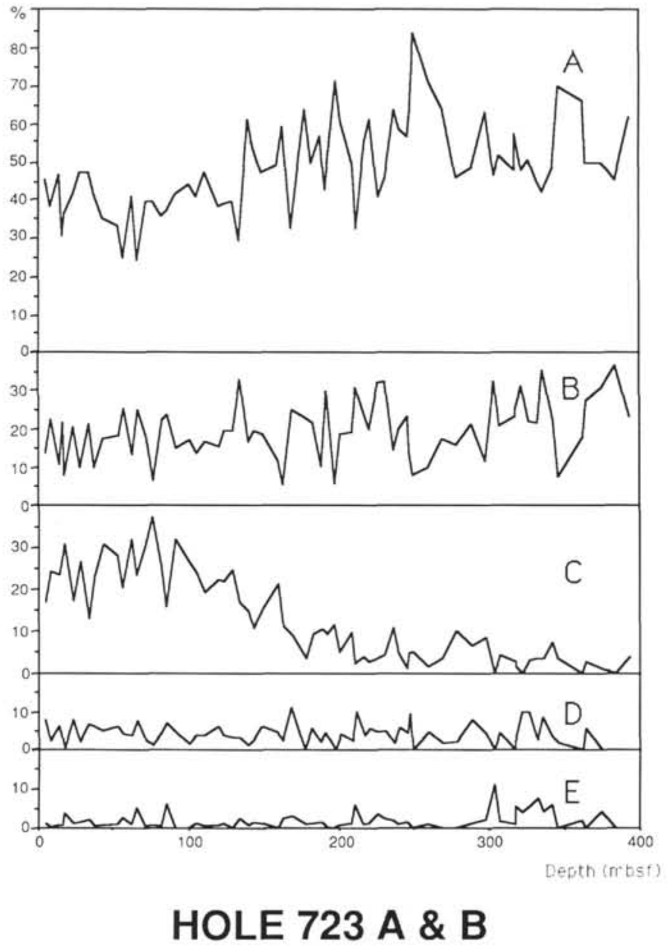

Figure 3. Percentages of dominant pollen types and Monsoon Pollen Index (MPI) in Holes 723A and B combined. **A.** Chenopodiaceae. **B.** Gramineae. **C.** *Artemisia*. **D.** Cyperaceae. **E.** MPI.

climatic changes is feasible, as the amount of palynomorphs in the studied sediments is adequate for pollen analysis.

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APPENDIX A
List of Pollen Types Recovered in Holes 721B, 723A and 723B

Abies
Acacia
Acanthaceae
Acer
Alchornea
Alismataceae
Alnus
Araliaceae
Artemisia
Asphodelus
Balanites
Betula
Bhoeravia
Blepharis
Cadaba
Calligonum
Capparidaceae
Carissa
Caryophyllaceae
Cassia cf.
Celastraceae
Celtis
Centaurea
Chenopodiaceae
Cleome
Combretum
Commiphora
Compositae tub.
Compositae lig.
Convolvulus
Corchorus
Corylus
Cruciferae
Cupressus
Cyperaceae
Dodonea viscosa
Ephedra
Ephedra distachya
Ephedra fragilis
Erica
Euphorbia
Fagus
Fraxinus
Gramineae
Heliotropium
Hippophäe rhamnoides
Indigofera
Jasminum abyssinicum
Justicia
Labiateae
Ligustrum
Liquidambar
Maerua
Mallotus
Mercurialis annua
Mitracarpus
Myrica
Nauclea
Neurada
Nitraria
Olea
Onobrychis
Papilionaceae
Peristophe
Pinus
Pistacia
Plantago
Plumbaginaceae
Plumbago
Podocarpus
Polygala
Polygonum senegalense
Prosopis
Quercus
Reseda
Rhamnus
Rhizophoraceae
Rhus
Ricinus
Rosaceae
Rubiaceae
Rumex
Sapotaceae
Solanaceae
Spores monolete
Spores trilete
Tribulus
Typha
Ulmus
Umbelliferae
Urticaceae
Zygophyllum