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Climate and environmental change at the end of the Holocene Humid Period: A pollen record off Pakistan

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Abstract

Pollen studies from core SO90-56KA recovered from the Arabian Sea off the Makran Coast (24° 509N, 65° 559E; 695 m depth) show that the end of the Holocene Humid Period, linked to the weakening of Indian monsoon fluxes, took place between 4700 and 4200 BP. Two periods of strong summer monsoon activity are identified between 5400–4200 BP and 2000–1000 BP during which the montane pollen taxa coming from the Himalayas reached the Makran coast due to increased fluvial activity of the Indus River. A contrasting period, dominated by the winter monsoon between 4200 and 2000 BP, is identified based on the presence of pollen taxa from the Baluchistan plateaus. The regional vegetation of the low- and midaltitudes, arid and semiarid, are remarkably stable from 4500 BP to the present. ***To cite this article: S.J. Ivory, A.-M. Lézine, C. R. Geoscience 341 (2009).***

Résumé

Le climat et les changements environnementaux à la fin de la période humide de l'Holocène : une archive palynologique sur la marge continentale du Pakistan. L'analyse pollinique de la carotte SO90-56KA prélevée en mer d'Arabie au large de la côte du Makran (24° 509N, 65° 559E ; 695 m profondeur) montre que la fin de la période humide holocène, liée à l'affaiblissement des flux de la mousson indienne d'été se situe entre 4700 et 4200 BP. Deux périodes de forte activité de la mousson d'été sont identifiées entre 5400 et 4200 BP, puis entre 2000 et 1000 BP, au cours desquels les taxons polliniques montagnards himalayens atteignent les côtes du Makran, en relation avec une activité fluviatile accrue de l'Indus. Une période au contraire dominée par la mousson d'hiver est identifiée entre 4200 et 2000 BP par la présence de taxons polliniques en provenance des plateaux du Balouchistan. La végétation régionale des basses et moyennes altitudes, aride à semi-aride, est restée remarquablement stable de 4500 BP à aujourd'hui. ***Pour citer cet article : S.J. Ivory, A.-M. Lézine, C. R. Geoscience 341 (2009).***

Keywords: Pakistan; Holocene; Pollen; Paleoclimate; Indian monsoon; Paleovegetation; Marine core

Mots clés : Pakistan ; Holocène ; Pollen ; Paléoclimat ; Mousson indienne ; Paléovégétation ; Carotte marine

1. Introduction

The climate variability at the end of the Holocene Humid Period has often been cited to explain the

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major ''cultural crises'' observed in western Asia such as the demise of the Akkadian empire [7] in the Arabo-Persian Gulf or the abandonment of Harappan cities [27] in the Indus valley. Millennial- or centennial-scale arid–humid climate alternations [14,18], abrupt events [7], or more gradual tendencies of continual decline [6], have been reported superimposed on the long-term Holocene climate trend from wet to dry, linked to the progressive weakening of the Indian monsoon. In such arid environments, continental records of past climate change are extremely rare and often discontinuous with several millennia of environmental history lacking at the top of lacustrine sedimentary sequences [15,19] or hiatuses in the speleothem isotope records [12]. The only continuous records available come from marine sequences. Sediment core SO90-56KA from the northern Arabian Sea (24° 509N, 65° 559E; 695 m water depth), provides a well-dated, annually laminated record of the last 5400 years [30]. However, the origin and formation of the laminae in these sediments remain poorly understood [26,31] which makes it difficult to infer regional climate changes. This core has been studied for sedimentological and geochemical content [8,17]. Here we present the study of pollen content. The goal of our study is to trace back the end of the Holocene Humid Period as well as the installation of modern subdesertic conditions, and to detect small amplitude environmental and/or climate variations from 5400 cal BP to the present.

2. The modern setting

The climate of Pakistan and northeastern Arabian Sea is controlled by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ) (Fig. 1). In the summer (June–September), southwesterly winds transporting large quantities of moisture from the Indian Ocean reach the Indian subcontinent and are responsible for heavy rainfall; whereas, during winter (December–March), northwesterly winds prevail over northwestern India and Pakistan, bringing little to no precipitation whatsoever. As a result, large differences in seasonal precipitation distribution are observed with strong impact on plant distribution. In contrast with the western slopes of the Himalayan plateaus in the east, which receive up to 1500 mm of rainfall per year, the northwest lowlands along the coast and the Baluchistan plateaus, which are too far north for summer rain, receive only very little rainfall (less than 200 mm per year) during the winter months. This uneven geographical rainfall distribution, coupled with elevation, determines the repartition of most vegetation types. Mangroves, occurring in restricted areas along the coast, are mainly composed of *Avicennia marina*, the most adapted species to salt concentration and dryness, which also expands northwards into the Arabo-Persian Gulf [25]. *Rhizophora mucronata, Ceriops tagal*, and *Bruguiera conjugata,* which are adapted to wetter conditions, also occur at the mouth of the Indus River to the south. Tropical thorn forests [21,22], comprised mainly of semiarid grasslands and wooded grasslands with *Acacia* spp.*, Prosopis cineraria, Tamarix dioica*, and *Salvadora persica*, associated with *Euphorbia* spp., xerophytic species of Amaranthaceae, *Calligonum polygonoides, Cassia* spp. and halophytes such as *Suaeda fruiticosa* and *Salsola foetida,* occur in most of the country from sea-level to around 1000 m in altitude. Montane forests expand on the western slopes of the Himalaya range to the east and the Baluchistan plateaus to the north. Four main vegetation belts are observed on the Himalayan slopes according to altitude and precipitation received during the summer monsoon. Dry subtropical mixed scrub forest primarily composed of *Olea cupidata*, *Acacia* spp., and *Dodonaea viscosa* are found from 1000 to 1500 m. Between 1500 and 3300 m lie subtropical pine forest and Himalayan moist temperate forest with *Pinus gerardiana*, *Cedrus deodorata, Picea morinda*, and *Abies pindrow* occasionally associated with deciduous oak *(Quercus incana, Q. dilate, Q. semecarpifolia)*, *Alnus* spp., *Acer* spp. and other broad-leaf deciduous trees and shrubs in moist places. Himalayan dry coniferous forest starts above 3300 m with *Cedrus deodorata, Picea morinda, Pinus gerardiana*, and evergreen oak (*Q. ilex)*. Above the treeline extend alpine scrubs with *Juniperus* spp., *Artemisia* spp., and *Ephedra intermedia*. The Baluchistan plateaus of Northwest Pakistan, above 1500 m, are subjected to extremely dry conditions, due to the dominance of winter monsoon fluxes, and support an open vegetation of juniper forests as well as some dry tropical and temperate semievergreen scrub forest. This area is dominated by *Juniperus macropoda*, *J. semiglobosa*, and *J. seravschanica* in association with *Pistachia* spp., *Prunus* spp.*, Berberis* spp.*, Lonicera* spp.*, Lycium barbarum*, and *Artemisia* spp.

The core site (SO90-56KA) is located in the Arabian Sea in an Oxygen-Minimum Zone (OMZ) on the continental margin about 60 km south of the Makran Coast in Baluchistan (Fig. 1; [30]). The area is subject to input from local rivers which drain the Makran coast and the Baluchistan plateaus to the north [17] and from the Indus River to the south, which, with a length of over 3000 km, is the third longest river in the world and

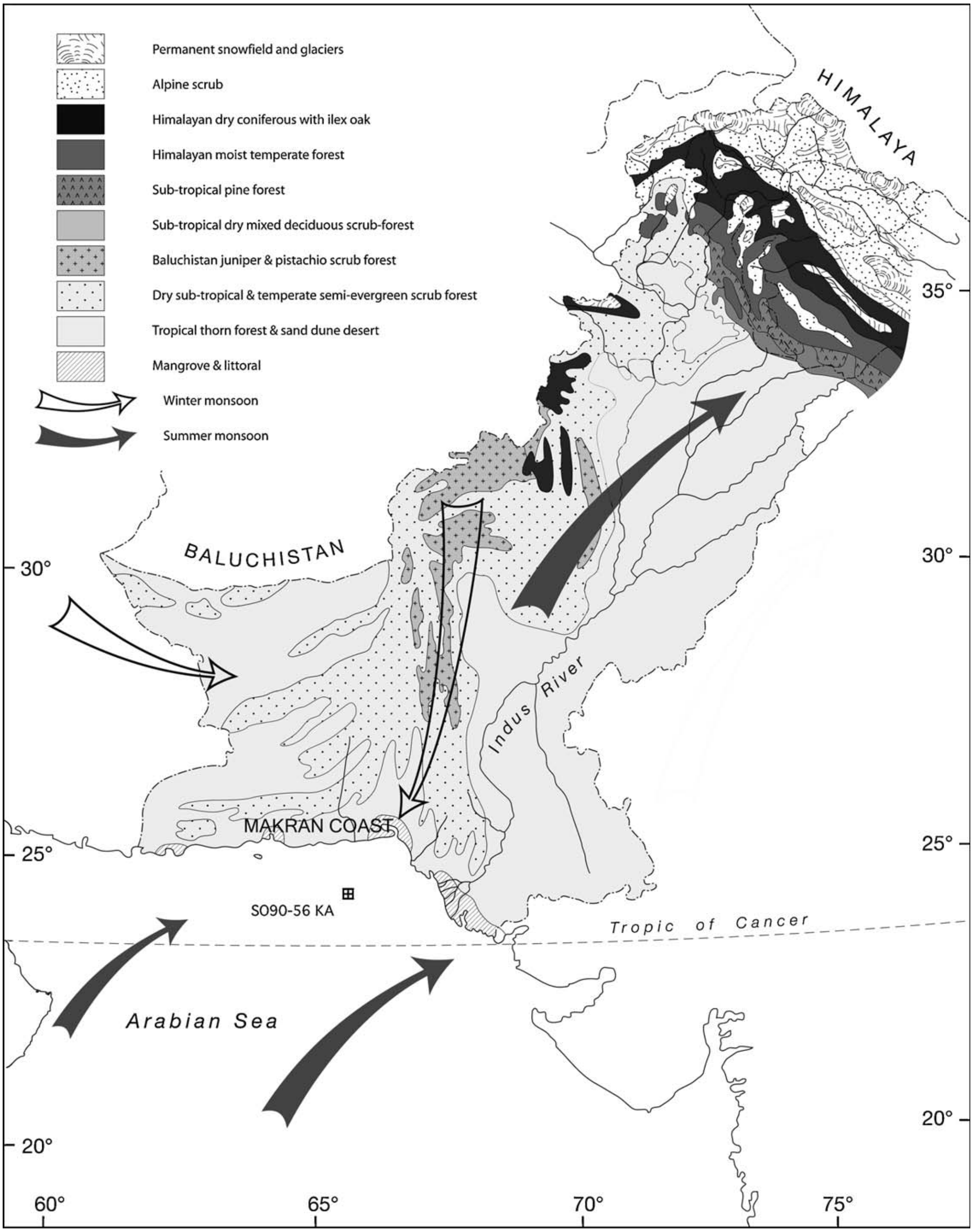

Fig. 1. Map of present-day vegetation zones in Pakistan (adapted from Roberts [21]) including seasonal monsoonal wind patterns and position of core SO90-56KA in relation to the Indus Delta and the regional Makran Rivers, shown east and north of the core site.

Fig. 1. Végétation actuelle du Pakistan (carte adaptée de Roberts [21]) incluant la circulation atmosphérique et la localisation de la carotte SO90-56KA, en relation avec le delta de l'Indus et des fleuves locaux de la côte du Makran à l'est et au nord.

drains an area of 950,000 km^2. The Indus River and its main tributaries first cross the Himalaya before creating a wide alluvial plain that becomes a typical fan-like delta as it meets the Arabian Sea.

3. Materials and methods

Marine core SO90-56KA was sampled at 10 cm intervals for pollen and organic microdebris studies. All samples (volumes: 1.5–2.5 cm^3) were processed using standard methods according to Faegri and Iversen [11] and sieved at 5 μm. Exotic lycopods have been included in order to calculate concentrations and influx values (Fig. 4A). Counts ranged from 216 to 553 pollen grains per sample with no barren samples, and influx values ranged from 686 to 3450 grains per cm^2 per year. The determination of 116 pollen taxa was made using the African Pollen Database reference collection and several atlases of pollen morphology [4,9,20]. The presence of algae was recorded separately. Percentages were calculated against a sum including all terrestrial taxa identified (both pollen and fern spores) except undeterminable grains and mangrove pollen types, which were calculated separately on the total grains counted (Figs. 2–4B). Nonsignificant variations recorded by the most characteristic taxa were avoided by the use of four sample running mean values of pollen percentages. Percentage diagram, Fig. 2, was drawn using TILIA 2.0 [13] from an age model based on varve counts, calibrated by 16 conventional and AMS ^{14}C measurements on planktonic foraminifera [30]. The resulting time resolution ranges from 10 to 125 yr. Zonation of the pollen diagrams was done with CONISS [13].

4. Description of the results

Most of the vegetation associations encountered in Pakistan are represented in the pollen assemblages from core SO90-56KA: the lowland xeric communities dominate in both percentages and diversity with, among others, Amaranthaceae–Chenopodiaceae undiff., *Artemisia*, Asteraceae undiff., *Calligonum, Salvadora persica*-type, *Acacia,* and *Prosopis*. In addition, the mangrove forests are represented by *Avicennia marina*, Rhizophoraceae (*Rhizophora, Ceriops tagal* and *Brughiera*-type) and Combretaceae undiff. The middle altitude woodlands from the Himalayan slopes are mainly represented by *Olea* associated with *Acacia*, while *Juniperus*-type originates mostly from the Baluchistan plateaus. Upland forests of the Himalaya are represented by *Alnus, Betula, Alchemilla, Cedrus* and *Pinus*. Some pollen types may originate from several plant communities such as *Ephedra,* which may occur in the lowlands, particularly along the coast, but

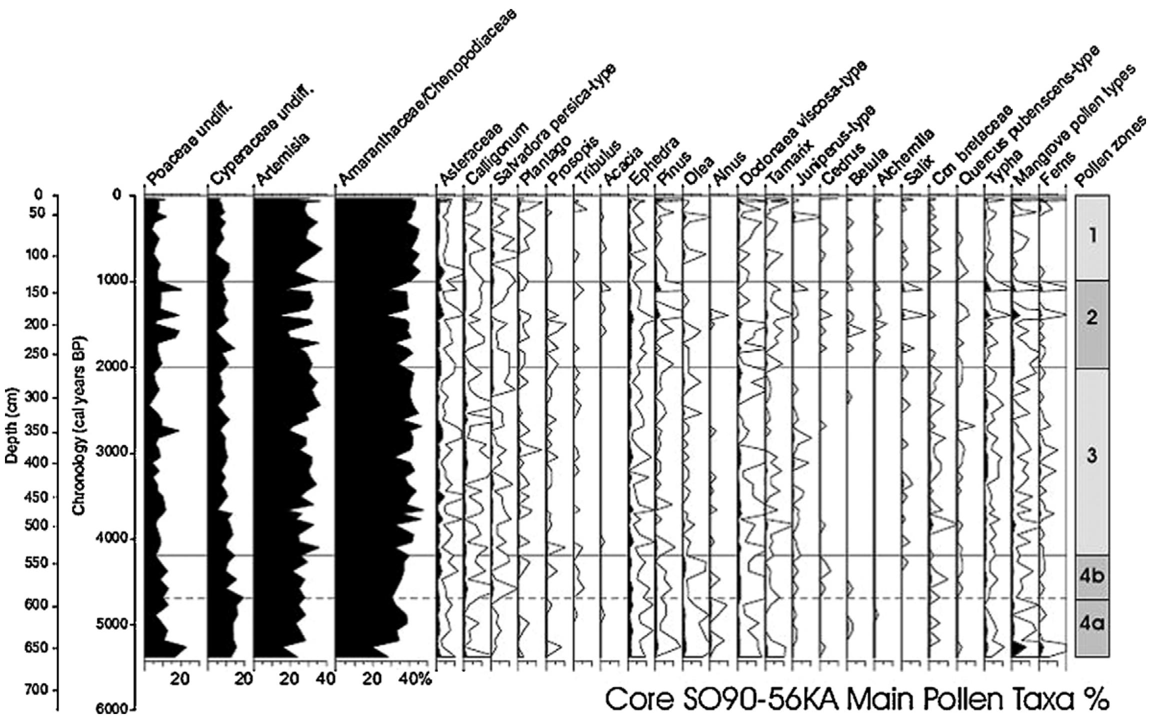

Fig. 2. Simplified pollen percentage diagram for core SO90-56KA. Zonation is based on CONISS analysis [13]. Pollen taxa names are based on those from the African Pollen Database. All white curves represent an enlargement of 10 ×.

Fig. 2. Diagramme pollinique simplifié de la carotte SO90-56KA. La zonation est réalisée à l'aide du logiciel CONISS [13]. La taxonomie pollinique est celle de la Banque africaine de données polliniques. Les courbes blanches montrent une exagération dix fois supérieure des valeurs de pourcentage.

also in the alpine belt of the Himalaya, and *Dodonaea viscosa*-type, which expands on both the Himalayan slopes and the Baluchistan plateaus. The origins of such taxa can be discerned by matching the important pollen taxa for a certain zone to known vegetation associations from each source area.

Except Amaranthaceae–Chenopodiaceae undiff., *Artemisia*, Poaceae undiff., Cyperaceae undiff., and Asteraceae undiff., which largely dominate the pollen sequence with maximum values of 47, 37, 23, 20 and 5% respectively, the other pollen types rarely exceed a few percent. However, changes in these rare types can be used to define four main pollen zones (Fig. 2):

- from 5400 to 4200 cal yr BP, zone 4 has been divided into two subzones at 4700 cal yr BP. The whole of zone 4 is characterized by the occurrence of *Olea* (2%), *Alnus* (0.9%), *Alchemilla* (0.2%), *Betula* (0.3%), *Pinus* (1.5%), *Cedrus* (0.6%) and *Ephedra* (2.8%), the association of which suggests an origin in the Himalayan highlands. In addition, Poaceae shows its highest value (25%) in subzone 4a, but immediately begins to decrease until the start of subzone 4b, when it recovers (13%) slightly and stabilizes for the rest of the zone. Cyperaceae is prevalent throughout subzone 4a (17%), but begins steadily to decrease (9%) at the onset of subzone 4b. Also during this phase, most freshwater indicators are abundant including mangrove pollen types (8%) and ferns (2.5%) at their maximum values, as well as influx of freshwater algae as high as 673.96 grains per cm^3 per year. Showing the reverse trend compared to the freshwater taxa, Amaranthaceae–Chenopodiaceae pollen types begin at their lowest values (22%) but jump quickly in subzone 4a and steadily rise to dominance by the end of subzone 4b (37%) as well as several mainly desert taxa including *Calligonum* (2%) and *Salvadora persica* (1.5%), that appear for the first time at the beginning of subzone 4b;
- from 4200 to 2000 cal yr BP, zone 3 shows a decrease of montane forest and freshwater taxa, whereas pollen types from dry low- and midland vegetations increase noticeably suggesting that a new pollen source dominates the input to the core site. This zone is characterized by a rise in *Juniperus* (max.: 1%), *Dodonaea viscosa*-type (max.: 2%), which mainly originate from the dry or xerophytic vegetation from Baluchistan in association with *Ephedra* (max.: 3%) that likely suggests a similar origin (see above vegetation description). A xeric element is present in the local vegetation also with dominance of Amaranthaceae–Chenopodiaceae (47%) and *Artemisia* (35%) as well as high values of *Calligonum* (max. 2%) and *Salvadora persica*-type (max.: 1%);
- from 2000 to 1000 cal yr BP, zone 2 is characterized by the reappearance of extraregional vegetation from the Himalayan highlands. This period shows maximum percentages of pollen types from parent plants found mostly in alpine and subalpine altitudes (*Alchemilla* max.: 0.7%, *Betula* max.: 1%, *Ephedra* max.: 3% [see above vegetation description]), while *Olea* (1%) and *Alnus* (1%), tree species at lower attitudinal belts in the mountains, are less important. Also notable is the surge in mangrove taxa and *Typha* in this zone. However, subarid and arid species remain important. Amaranthaceae–Chenopodiaceae is dominant, ranging from 28 to 43%, following a similar trend as *Artemisia. Prosopis, Tamarix, Salvadora persica*-type, *Calligonum* represent the lowland arid and subarid vegetation with maximum percentages of 1 to 1.6;
- from 1000 cal yr BP to the present, in zone 1, Amaranthaceae–Chenopodiaceae and *Artemisia* dominate the assemblage with maximum values of 46 and 38%. All freshwater taxa are low, with the exception of the very upper part of the sequence which also displays a coincident increase in input of most principal taxa. The extraregional taxa are difficult to interpret probably due to series of rapid changes. For example, though final values of *Salvadora persica*-type, *Calligonum*, and *Ephedra* are relatively high, all three taxa vary significantly throughout this thousand year period. A higher resolution study would be needed to elucidate the effects of shorter-term climatic events on the low- and midland vegetation during this period.

5. Interpretation and discussion

Core SO90-56KA pollen record shows that semiarid conditions prevailed in the Makran area from the beginning of the period studied to the present as recorded by the continuous occurrence with high values of steppic herbaceous pollen types. This result is consistent with other paleoenvironmental records showing the complete desiccation of lakes after 5500 cal BP in southern Arabia [16], in the Thar Desert, northwestern India [10] and the widespread extension of dry environmental conditions [2].

The opposite trend of the most arid pollen types (e.g., Amaranthaceae–Chenopodiaceae), which increase progressively, in relation to the wettest (e.g., Cyperaceae) in core SO90-56 KA (Fig. 3) suggests that the aridification process which led to the installation of

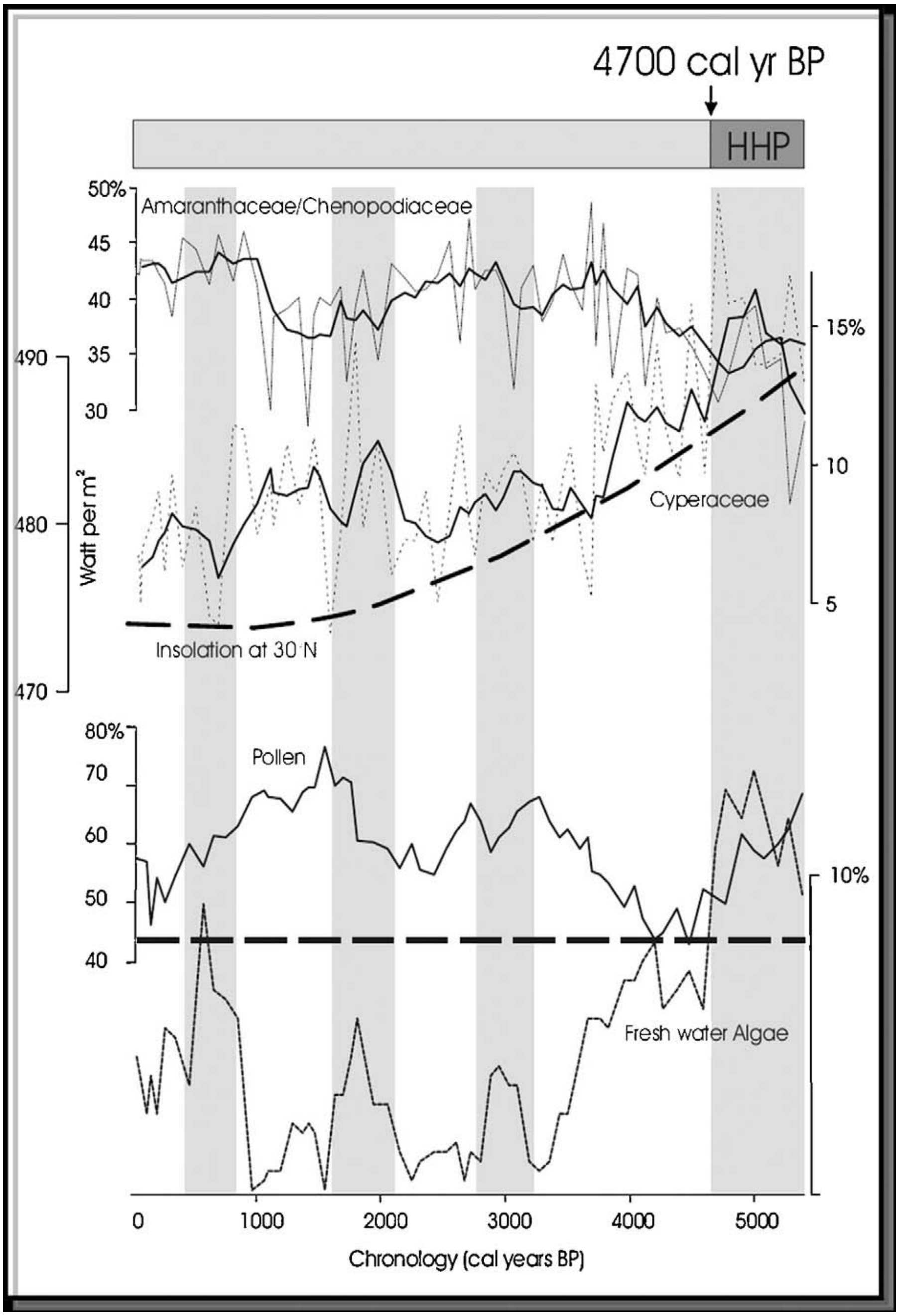

Fig. 3. Opposing trends of decline in humid indicators (ex. Cyperaceae) and coincident increase of regional arid and xerophytic species (ex. Amaranthaceae–Chenopodiaceae) around 4700 cal yr BP showing the weakening of summer monsoon fluxes associated with the end of the Holocene Humid Period (top). The former is shown against a curve representing summer insolation at 30°N. Comparison of percentages of pollen versus freshwater algae (bottom), calculated on the sum of all pollen and algae, shows decline of freshwater input to the core site around 4700 cal yr BP.

Fig. 3. Tendances opposées des indicateurs d'humidité (représentés par la courbe des pourcentages de Cyperaceae) et des indicateurs d'aridité (représentés ici par la courbe des pourcentages d'Amaranthaceae–Chenopodiaceae) autour de 4700 cal BP, montrant l'affaiblissement des flux de la mousson indienne d'été à la fin de la période humide holocène (en haut). La décroissance des valeurs d'humidité coïncide avec celle de l'insolation d'été à 30°N. La comparaison des valeurs de pollen et des algues d'eau douce (en bas) confirme le déclin des apports fluviatiles après 4700 cal BP.

modern environmental conditions was gradual and followed the orbitally-induced long-term decrease of summer monsoon fluxes. The noticeable contribution of all the humid indicators, particularly of freshwater algae and *Rhizophora* of coastal mangrove vegetation, in zone 4 most likely suggests that rivers significantly influenced the core site from 5400 to 4700–4200 cal yr BP. After this date, lower values of all the humid indicators suggest more discrete phases of freshwater flow to the ocean between 3200 and 2890 cal yr BP, between 1830 and 1090 cal yr BP, then during the last millennium around 615 cal yr BP. Due to reduced freshwater flow compounded by the very open, semidesertic vegetation, wind transport was likely the major pollen source from the low- and midlands of Makran to the core site from 4200 cal yr BP to the present. This result contradicts previous assumptions based on varve thickness measurements and geochemical analyses [17,30], which suggest the dominance of river runoff during all of the last 5400 years.

One of the most striking features of our pollen record is the contribution of high altitude vegetation associations, transported to the core site from Baluchistan in the north or the Himalayas in the east. Pollen originating from parent plants in the local vegetation of the low- and midaltitude can be transported either by the local Makran rivers or northwesterly winds, which blow southward during the winter months from Baluchistan to the coast. Conversely, extraregional pollen taxa which occur uniquely in the eastern mountain regions cannot possibly be transported by wind to the core site. The summer monsoon winds in Pakistan blow in a northeasterly fashion, towards the mountains and away from the coast; however, the increased precipitation brought by the monsoon winds to the Himalaya contribute to greater effect of Indus fluvial input to the Arabian Sea. The presence of extraregional montane taxa in these pollen assemblages indicates the role of the Indus River in sedimentation at the core site. This led to the characterization of three main periods (Fig. 4A,B):

- between 5400 and 4200 cal BP (zone 4), the occurrence of pollen grains which originate from subtropical evergreen and moist temperate forests together with freshwater indicators suggests that abundant rainfall occurred between 1000 and 3000 m alt. on the western slope of the Himalayas in relation with enhanced summer monsoon fluxes of SW–NE direction. This led to increased activity of the Indus River which drains the corresponding vegetation belts and the transport of pollen grains from these belts to the ocean;
- centred around 1500 cal yr BP (zone 2), a similar pattern as seen in the previous period 5400–4500 cal BP demonstrates a short phase of strengthened southwest monsoon rains. However, the pollen content shows that the source zone of extraregional elements was not restricted to middle elevations as before, but concerned also probably higher vegetation belts, including the alpine scrubs. This period has been described by Luckge et al. [17] as the wettest period of the last 2000 years. Though the transport of these alpine pollen taxa suggests enhanced Indus River input to the site, pollen data from xeric plant communities, particularly the high values of *Prosopis*, suggest that dry conditions persisted in the lowlands;
- the period lasting from 4200 to 2000 cal yr BP displays a quite different pattern. Throughout this time humid indicators and montane taxa are poorly represented suggesting overall dry conditions and lowered Indus River transport. The former is also confirmed by the high influx values of pollen from xeric lowland ecosystems: Amaranthaceae–Chenopodiaceae, *Artemisia, Calligonum, Salvadora persica*-type, *Ephedra.* Long-distance pollen grains from the Himalaya are scarce and replaced by *Juniperus* and *Dodonaea viscosa* which mainly originate from the Baluchistan plateaus. We therefore assume that this period was mainly influenced by dominance of winter monsoon fluxes in a north–south direction with low rainfall. These winter fluxes reach their maximum strength between 3500–3000 cal BP followed almost immediately by the most arid phase in this record up until 2000 cal BP. The influxes of almost all taxa are low suggesting that both winter and summer rain are strongly diminished. This is also characterized by Luckge et al. [17] as the driest period of this record.

At the end of the heightened southwest monsoon period centred around 1500 cal BP, influx of all plant taxa declines abruptly until 1000 cal BP. Due to this coincident decline in influx values, percentage data can be difficult to interpret; however, it is clear by the very low percentages of freshwater taxa that river transport is probably limited. Even aeolian transport seems limited as pollen assemblages are dominated by Amaranthaceae–Chenopodiaceae despite its unusually low influx values. Our data agree with geochemical analyses from Luckge et al. [17] which show very low fluvial input at the time despite the dominance of winter rain and likely suggest that summer rains were absent and winter rains minimal. Vegetation resembles that of the Baluchistan steppe; however, unlike during the period of stronger

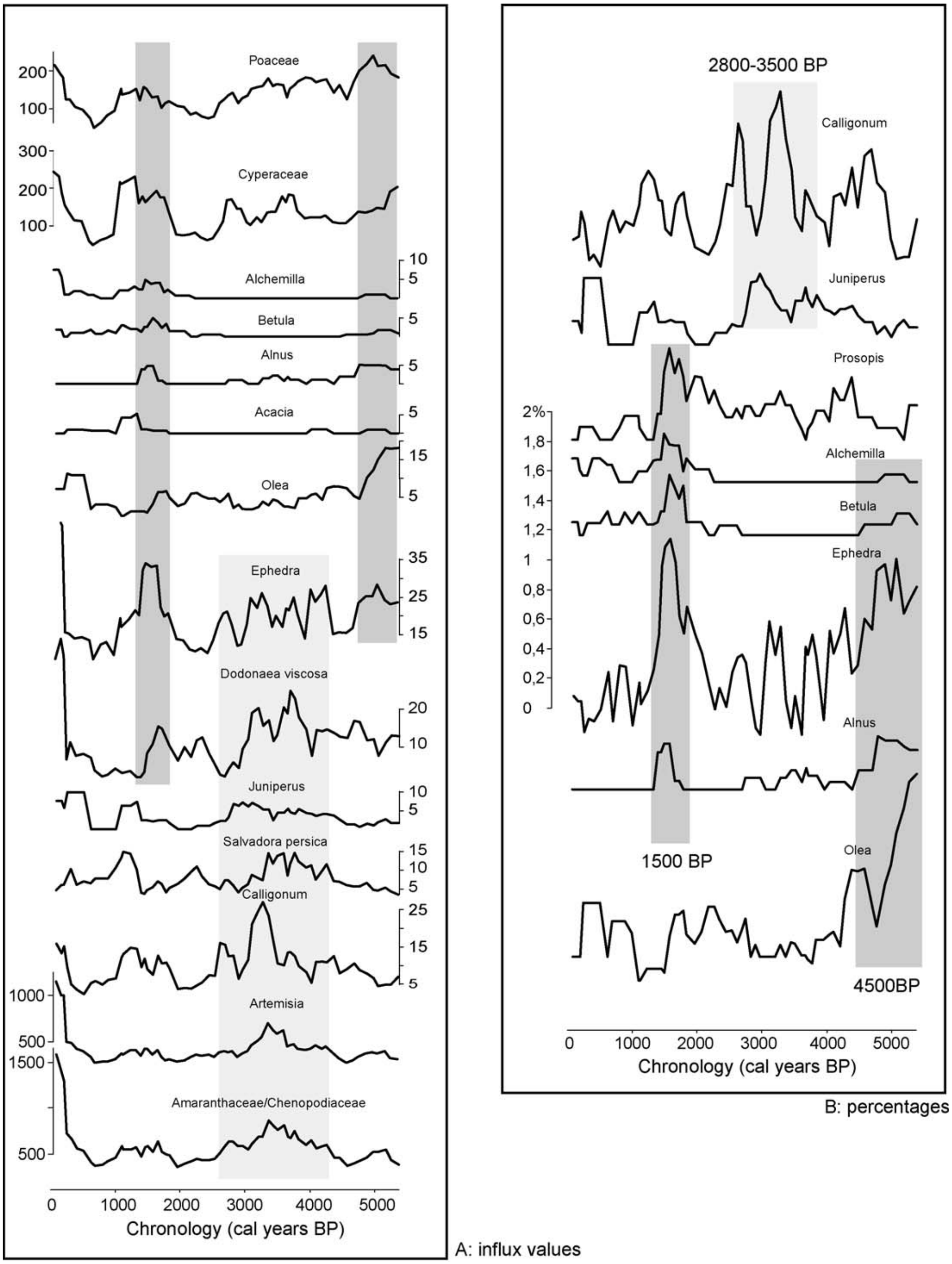

Fig. 4. Influx (**A**) and percentages (**B**) values of regional and extraregional pollen types. Dark grey boxes indicate periods of strengthened summer monsoon (centred around 4500 and 1500 cal yr BP) associated with increases in regional humid indicators and extraregional pollen of Himalayan origin transported by the Indus River. The light grey box indicates strengthened winter monsoon fluxes (2800–3500 cal yr BP) shown by the increase of regional arid and xerophytic pollen types and extraregional pollen types wind-transported from Baluchistan.

Fig. 4. Valeurs d'influx (**A**) et de pourcentages (**B**) de types polliniques régionaux et extrarégionaux. Les boîtes gris foncé indiquent les périodes de forte mousson d'été (centrée autour de 4500 et 1500 cal BP) associée à l'augmentation des indicateurs d'humidité et de grains de pollen transportés depuis les hauts plateaux himalayens par le fleuve Indus. Les boîtes gris clair indiquent une période de forte mousson d'hiver (2800–3500 BP) révélées par l'augmentation des valeurs de taxons xérophytes et extrarégionaux en provenance du Balouchistan.

winter rain from 4200–2000 cal yr BP, very few lowland tree species are recorded and even *Calligonum*, which grows on dunes, is not well represented.

In the SO90-56KA core, the last millennium displays a more complicated pollen signal which is most likely due to high variability of the monsoon during this period as recorded by sea-surface temperatures and salinity [8]. A higher resolution study would be required to provide enough detail to interpret this period. At the very end of this sequence, influx values show an abrupt and dramatic peak in most taxa. This episode of sudden high pollen input to core site is probably based on short-term oscillations as it is not recorded in most of geochemical analyses of Luckge et al. [17]. It is possible that an increase in wind activity is to blame. However, Treydte et al. [29] found increased rainfall in the mountains of East Pakistan and nearby northern Arabian Sea [1] starting from the beginning of the twentieth century. This signal is also seen in the Ti/Al ratio, an index of fluvial input from the nearby Makran Rivers [17]. If high rainfall in the Himalaya had been coincident with strengthened winter rain in the last century, the increase in transport alone could account for the unusual peak in pollen input.

6. Conclusion

Core SO90-56 KA pollen record reveals centennial-to millennial-scale climate variations superimposed on the long-term trend of Northern Hemisphere insolation decrease during the last few millennia (Fig. 3). The end of the Holocene Humid Period dominated by summer monsoon rains is dated between 4700–4200 cal yr BP that predates by about 1000 years previous observations from marine [3] or continental [5,23,24,28] pollen records from NW India. After a dry phase dominated by winter monsoon fluxes, a brief return to summer monsoon dominated fluxes is observed around 1500 cal yr BP. The climate of the last millennium appears to have been highly variable and more data is required to precisely trace the influence of events such as the Little Ice Age or the Medieval Warm Period.

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