Climatic fluctuations during Holocene in Kusumelli Swamp, central Narmada Valley, India

The Quaternary sequences of central Narmada Valley of India preserve a great wealth of diverse mammalian fossils including not only the oldest hominin fossil[1,2] but also a wide range of palaeolithic tools[3]. In spite of witnessing human evolution, social complexities and techno-cultural advancement since late Pleistocene with changing climate under prominent Asian SW monsoon region, palaeovegetational and palaeoclimatalogical studies have not been attempted except by Nandi[4] and Patnaik *et al.*[5]. In the present study, an attempt has been made to reconstruct the vegetation scenario and climatic fluctuations on the basis of pollen proxy data in Kusumelli Swamp, central Narmada Valley, India during Holocene (Figure 1).

The climate in central India has been broadly classified into four seasons: (i) winter (January–February), (ii) hot summer (March–May), (iii) rainy southwestern monsoon (June–September) and (iv) post (northeast) monsoon (October–December)[6]. The area experiences maximum temperature in May (34.4°C) and minimum temperature in December–January (19.1°C). About 92.8% of the annual rainfall (1225.9 mm at Hoshangabad) is received during southwest monsoon seasons and only 7.2% of the annual rainfall takes place during the October–May period[7].

Central India which possesses approximately 24.66% of the total forest cover of the country has not received adequate attention to understand the antiquity of the tropical deciduous forests, the role of climate fluctuations on these forests and their impact on human inhabitation and behaviour except some information available from northeastern part of Madhya Pradesh[8–12].

Broadly, the vegetation in this region is moist and dry tropical deciduous forests. The tropical moist deciduous forests are characterized by *Shorea robusta*, *Tectona grandis*, *Terminalia arjuna*, *Anogeissus latifolia*, *Adina cordifolia*, *Syzygium cumini*, *Lagerstroemia parviflora*, *Buchanania lanza*, *Mitragyna parvifolia*, *Schleichera oleosa*, *Butea monosperma* with some shrubby elements, viz. *Strobilanthes angustifrons*, *Clerodendrum viscosum* and *Symplocos*. The tropical dry deciduous forests mainly comprise *Holoptelea*, *Lannea coromandelica*, *Sterculia urens*, *Acacia* spp., *Boswellia serrata* and *Ziziphus mauritiana*. However, the study area and adjoining areas possess dry mixed deciduous forest dominated by *Tectona grandis*, *Butea monosperma*, *Diospyros melonoxylon* and *Buchanania lanza* with common trees such as *Madhuca indica*, *Manilkara hexandra* and *Mumusop elengi*[8].

Kusumelli Swamp (22°54′05.5″N and 77°48′39″E), Sehore district, Madhya Pradesh is located around 5 km north of Narmada river channel at the southern foot hills of the Vindhyan mountains within the alluvial deposits of central Narmada Valley. It is a perennial swamp of around 3 km periphery, fed by rain runoff water as well as seepage from adjacent Vindhyan mountains. Twenty six samples for pollen analysis and two samples for radiocarbon dating have been collected from 1.5 m core sediment profile by using Hiller's peat auger exposed at south western side of swamp. The uppermost part of the bore-core consists of black carbonaceous clay with few rootlets (25 cm) underlain by black carbonaceous clay (25 cm) followed by silty carbonaceous clay (70 cm) underlain by silty mud with calcretes (30 cm). On the basis of two dates, i.e. 8490 ± 100 yr BP (BS 2758) and 6140 ± 130 yr BP (BS 2574) from similar type of sediments, the sedimentation accumulation rate is determined to be 1 cm/47 years. The ^{14}C dates have been used to interpolate more dates, i.e. 11,900, 8500, 7000, 5100 yr BP, however, the younger sediments could have been eroded or deposited elsewhere in the swamp. The interpolated dates have been used for a more precise demarcation of vegetation change and fluctuations of climate on temporal scale in the region. The pollen/spores were extracted from core samples by using conventional method of acetolysis[13].

A total of 160–600 palynomorphs were counted per sample and percentage of each taxa has been calculated in terms of the total terrestrial plant pollen. The palynomorphs are organized in groups of trees, shrubs, herbs, ferns, algal and fungal remains in the pollen diagram. On the basis of the changing relative frequencies of major arboreal and non-arboreal taxa, the pollen diagram of Kusumelli Swamp has been divided into three zones (Zone-I to III) of vegetation and corresponding climate fluctuations (Figure 2).

Zone-I inferred between 11,900 and 8500 yr BP and is characterized by the

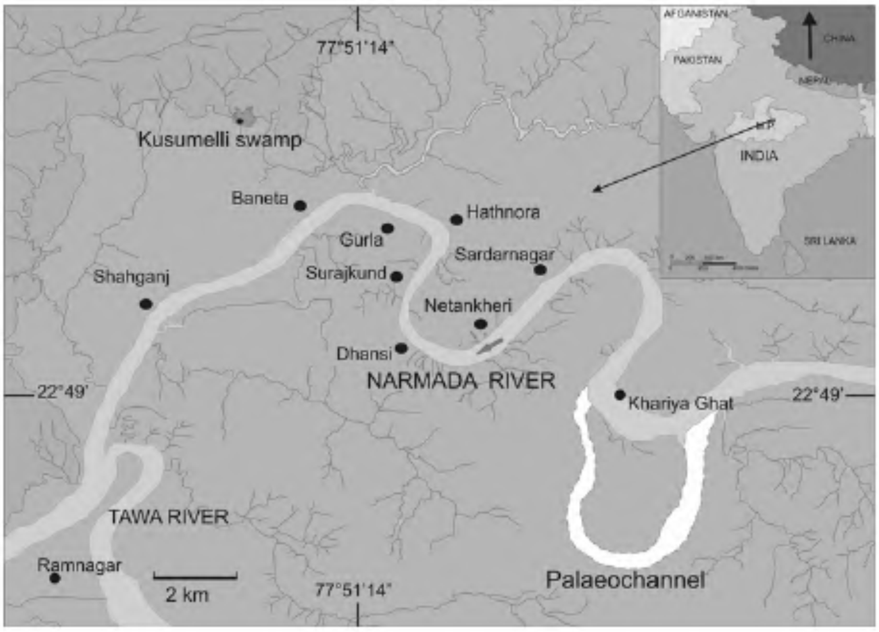

Figure 1. Location map of the area (Modified after Patnaik *et al.*[5]).

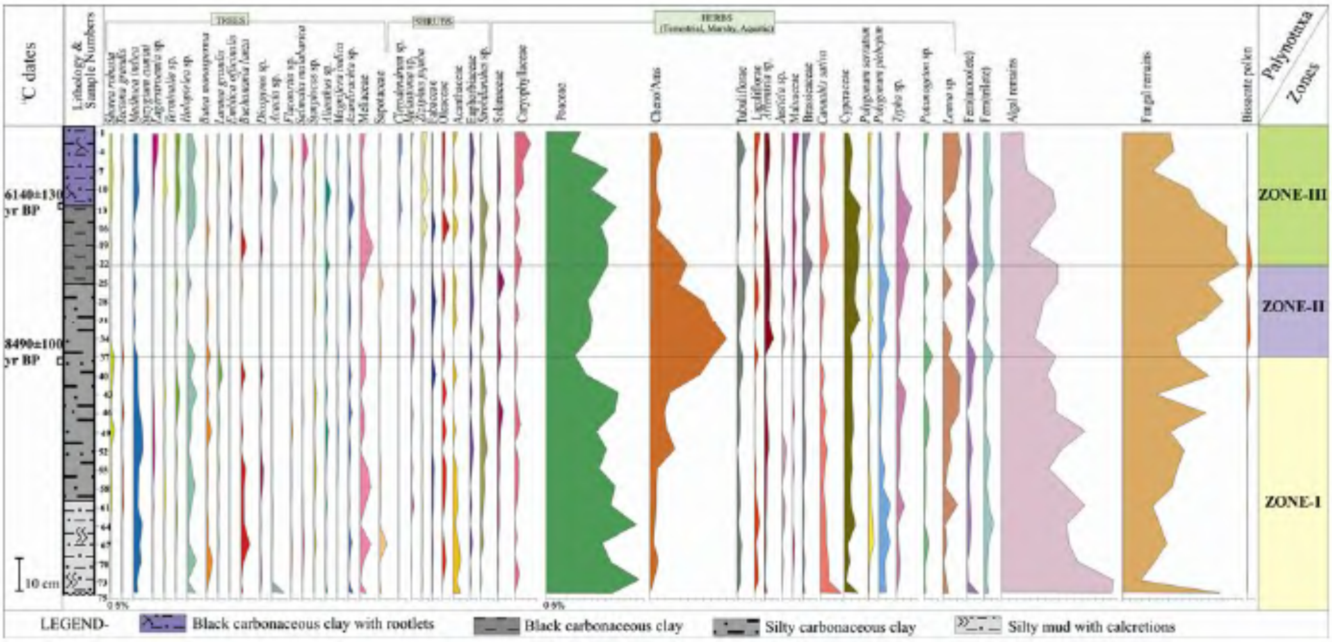

Figure 2. Pollen diagram of Kusumelli Swamp, Sehore district, Madhya Pradesh.

presence of moist deciduous taxa such as *Shorea robusta*, *Tectona grandis*, *Madhuca indica*, *Holoptelea*, *Butea monosperma*, *Buchanania lanza*, *Terminalia*, *Lannea grandis*, *Diospyros*, *Flacourtia*, *Acacia* and Meliaceae with some moisture-loving elements *Syzygium*, *Lagerstroemia* and *Salmalia malabarica*. The shrubs are represented by *Melastoma*, *Strobilanthes*, *Ziziphus jujuba*, Fabaceae, Oleaceae, Acanthaceae and Euphorbiaceae. Among the herbs, Poaceae is the dominant with relatively low frequency of Cheno/Ams. This condition reflects warm and moist conditions of the region and probably due to intense summer monsoon. Sedges (Cyperaceae) and other wetland taxa such as *Typha*, *Potamogeton* and *Polygonum* envisage the existence of locally large and highly waterlogging pond in the area. The overall vegetation pattern indicates that maximum vegetational concentration and diversity occurred during 11,900–8500 yr BP under warm and humid climate. This inference is associated with post-glacial intensification of SW monsoon, a climate shift also known as 'climate optima', leading to a dramatic increase in the atmospheric moisture and surface water availability at about 11–10 ka yr BP[14–18]. Zone-II represents 8500–7000 yr BP and is marked by the disappearance of few trees *Syzygium*, *Lagerstroemia, Diospyros*, *Acacia*, *Flacourtia* and *Salmalia malabarica* with decreased frequency of *Shorea robusta*, *Tectona grandis*, *Buchanania lanza*, *Lannea grandis* and again increased the frequency at the top. The assemblage represents tree-savannas that grew in the region and comprises grasses with high frequency of Cheno/Ams with sparsely distributed tress *Madhuca indica*, *Holoptelea*, *Butea*, *Terminalia* and Meliaceae. The change in vegetational pattern indicates that this region experienced a cool and dry climate with an ameliorating trend of climate during this phase[11]. The successive depletion in vegetation, relative low frequency of Poaceae with high frequency of Cheno/Ams and increased frequency of *Artemisia* around 8200 yr BP also implies the cooler and dryer climate. This climatic change can be related to 8.2 ka yr BP global short-lived cooling event, which is 'cool poles and dry tropics' pattern of short term[19]. This event was well documented in arid event of Africa, China, India and Pakistan[19,20]. Around 7000–5100 yr BP (Zone-III), the tree-savannas were invaded by dry deciduous forest elements of Zone-I; first appearance of *Emblica officinalis* and *Clerodendrum* and moist forest elements such as *Syzygium* and *Lagerstroemia* coupled with thickets of *Ziziphus jujuba*, *Melastoma*, Fabaceae, Euphorbiaceae and Acanthaceae. The enhancement in marshy taxa and aquatic element *Typha* indicates the expansion of swamp and waterlogging. The increased concentration and diversity of arboreal taxa implies favourable environmental conditions with sufficient precipitation for proliferation of dry deciduous forest under warm and humid climatic conditions. The change of vegetation from tree-savannas to mixed deciduous forests corroborates with the period of Climatic Optimum which has been witnessed globally around 7000–4000 yr BP[21].

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Developmental adaptation of leaves in *Podophyllum hexandrum* for effective pollination and dispersal

In alpine ecosystem, reproductive behaviour such as seed production and new plant establishment may be ineffective due to infrequent germination and low seedling survival[1–3]. On the other hand, clonal plants from alpine habitats reveal similar genetic variation as lowland species, suggesting that at least occasionally there is recruitment from seeds. Plant phenology can be a useful tool in describing micro-environmental differences between various habitats. Bliss[4] reported that many species in a specific habitat break dormancy, flower and fruit together, whereas the same species exhibits different cycles of development in other habitats. This shows the control of local micro-environmental factors on the pattern of plant development. Plants growing in alpine regions show unique phenology due to extreme environmental conditions. Temporal differences in snow disappearance determine the time of flower initiation and available growth period which affect reproductive success through the pollination process and the season length for fruit development[5–8]. Because air temperature changes as the season progresses, plants exposed by melting of snow at different times of the season experience different temperature regimes through the life cycle.

The activity level of pollinators has been shown to decrease significantly with increasing altitude, and diversity of insects species declines rapidly in the high temperate mountains. These findings have led to the hypothesis that predicts lower outcrossing rates and higher amount of autogamy or apomixis at high altitude, especially near the upper vegetational limits. Low temperatures and short snow-free periods which constrain the abundance and activity of insect pollinators[8,9], characterize arctic and alpine habitats. Thus, a relatively high proportion of arctic and alpine flowering plant species may have evolved autogamy and self-compatibility in response to poor cross-pollination opportunities. Self-compatibility co-evolves with changes in morphological or phenological traits of flowers that promote self-pollination[10].

Podophyllum hexandrum Roxb. ex Kunth. is a rhizomatous herb found growing in the sub-alpine region of the Himalayas. The distribution of this species varies from 2000 to 4000 m asl and the habitat ranges from alpine meadows and understorey of cedrus forest. The phenology of *P. hexandrum* is similar to that of other alpine and sub-alpine plants, where leaf emergence is at the onset of snow melt and dispersal of seed at the onset of winter. During winter, the plant is in its dormant condition and perenniates in the rhizomatous form. In spring, the plant has to produce flowers, successfully pollinate and reproduce/disperse seeds within a short span of 4 months. For effective propagation of this endangered species, it has an unusual combination of traits related to sexual reproduction. Most notably, it does not reward its native pollinators. The flower is large (3–6 cm in diameter), white, fragrant, bowl-shaped, with six petals, six stamens and a single, unilocular pistil with 50–150 ovules. The flower lacks nectar, but has abundant pollen. The flowers are protandrous; the anthers often dehisce before the flower has opened, stigmas remain receptive even as the stamens and petals abcise from the flower, approximately 1–2 weeks after anthesis. Factors such as prolonged stigma receptivity in plants at high elevation can offset reduction in pollination rates and make it comparable to pollinations at lower-elevation plants. For adaptation and perpetuity, the plant formulates effective adaptation, developmental modification for effective pollination and dispersal.

Immediately after the onset of snow melt, the rhizome sprouts and develops into first leaf (Figure 1 *a*) with a rich anthocyanin pigmentation which may function as a UV protectant or protect from herbivores since the leaf may not be visible due to the reflection of anthocyanin and also the leaf may not palatable. Within a few days the lobed leaves become greenish (Figure 1 *b*) and productivity is more during this stage (through podophyllotoxin production, pers. obs.). Later, the young green leaf forms a dark pigment from the centre (Figure 1 *c*) towards the periphery and is wholly pigmented within a few days of the first leaf formation. The pigmented secondary leaves develop from the base of the first leaves along with the flower (Figure 1 *d*). At this time only a prominently bright, white flower is visible with a dark, pigmented shrunken leaf providing contrasting background suitable for attracting pollinators. Within 3–4 days of anthesis, the petals and stamen wither-off and gynoecium remains 3–4 days after anthesis to receive more pollen, since the number