THE KOREAN JOURNAL OF QUATERNARY RESEARCH Vol. 23, No. 2, p.1-12 (December. 2009)

Review of Phytolith Research : Scope and Applications

Sanjay Eksambekar

Phytolith Research Institute Pune- 411033, India

1. Introduction

Most of the archaeobotanical and geo-archaeological contemplation's are confined to plant macrofossils, pollen and spores. The application of phytolith research is a complimentary aid towards enhancing the understanding of archaeobotany. Phytoliths can be extracted from the minerogenic deposits, which are usually less suitable for the reconstruction of the past vegetation through microfossils such as pollen and spores. Bioarchaeology has now emanated as an interdisciplinary subject that includes archaeobotany, archaeozoology, paleontology, and human osteology and to name a few disciplines like pollen analysis and phytolith analysis etc. Most of the archaeobotanical study is focused only on macro remains especially those of carbonised seed, wood charcoal and pollen preserved under various stratigrapic and climatic conditions.

2. Phytolith Insight

Phytoliths are the deposits of solid silica that are located in an intracellular and extracellular location of certain plant species. The term phytolith is a Greek word meaning plant stone; Phyto= Plant and Lithos= Stone. Numerous other terms have been proposed for silica bodies found in plants such as grass opal, opal phytoliths , plant opal or opaline silica. Opal phytolith production is wide spread in both monocotyledon and dicotyledons. Families well known as accumulators of silica bodies include Poaceae (grass), Cyperaceae (sedges) Ulmaceae (elm), leguminosae (bean), Cucurbitaceae (squash) and compositae (Sunflower family) (Metcalfe, 1960, 1971). However, now they are known to be widespread also in other families. Piperno (1988) reviewed the distribution of opal phytoliths from higher plats i.e. Angiosperms, Gymnosperms and Pteridophytes. There are some families, which yield less perceivable phytoliths. Such families characterized by poor silica accumulators include the chenopodiaceae, rubiaceae, araceae, cyclanthaceae, meloranatace and somolacaceae. The pattern of silica deposit can be found in almost any structure of the plant that serves as a storehouse of silica deposits. Morphological variation of phytoliths differs with multiplicity and redundancy. These variations occur by either production of many morphotypes in one taxon or occurrence of characteristic forms in many taxa (Rovner, 1971). Such variations are found in the morphotypes produced by various grasses (Mulholland 1989).

2.1. Silica Uptake in Plants

Silicon provides the raw material of phytolith formation. The soluble silica is mainly derived from the weathering of silicate minerals such as quartz and feldspar. Plants absorb silica through their roots. The silica solution along with other minerals is carried upwards to its aerial organs with the help of xylem the water conducting tissue. Silica in the soil solution enters into the plants in the form of monosilicic acid Si $(OH)_4$ (Piperno, 1988). This monosilicic acid in plant tissue is polymerized and forms solid deposits of silicon dioxide

(SiO_2) in the plant cell. This Polymerization occurs in the presence of supersaturated solution of monosilicic acid and is responsible for the formation of discrete phytolith shapes. Due to variation in the bond angle of amorphous silica they take any shape of the organic matrix (Bowdery, 1998), thus resulting in multiformatry of phytoliths.

2.2. Deposition of silica/phytoliths in Plant structures.

The deposition of solid silica within the plant organ is variable. In grasses, Phytoliths are derived mainly from the epidermal cell silicification, while in the Palmae and Morantaceae, phytoliths are mainly subepidermal in origin. In dicotyledons, epidermal tissue including hair cells, trichomes and hair bases are often the main locus for silicification. On the cellular level silica can have three loci of deposits namely the encrustation's of cell walls, in the interior of the cells (lumina), and in intercellular spaces. Most of the silica from roots is in the form of small nodular aggregates. Depositions of silica are found in various other parts of the plant namely the inflorescence (Parry and Smitson, 1964, 1966), Rhizomes and leafs (Sangster, 1985). They are also found in roots (Pease and Anderson, 1969), cork cells (Labouriau, 1983), leaf blades, sheaths, empty glumes, lemma, guard cells, subsidiary cells of stomata, trichomes, Xylem fiber tracheids and spirally thickened protoxylem (Jones and Handreck, 1967). Silica deposits are also located in the ray cells, and vertical parenchymatous cells of wood. Thus, various parts of the plant serve as a repository for silica deposit. These patterns are consistent within families and species with significant taxonomic and phylogenic character.

2.3. Chemical and Physical characteristics of phytoliths

Phytoliths are mainly composed of amorphous silicondioxide (SiO_2) with varying amount of water , ranging from 4 to 9%. Elements like aluminum (Al), iron (Fe), manganese (Mn), phosphorus (P), copper (Cu), nitrogen (N) and carbon (C) are present in the phytoliths in the form of occlusion, chemiabsorption or solid solution impurities. Occlusion of nitrogen and carbon in phytoliths could be due to the cytoplasmic material or the silica impregnation in the cellulose and lignin. Biogenic silica of plant is optically isotropic. The refractive index ranges from 1.41 to 1.47, with a specific gravity ranging from 1.5 to 2.4, and the colour ranges from colourless to light brown to opaque under transmitted light. Studies by Wilding *et al.* (1967) refer to a correlation between specific gravity and the colour of phytoliths that are occluded with carbon. Highly occluded phytoliths range between 1.5 to 2.0 sp.gr.

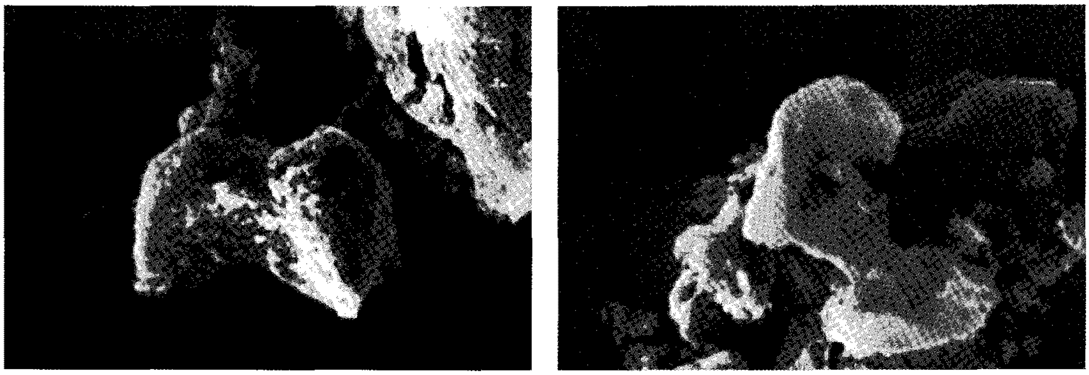

Fig. 1 Typical Panicoid dumbbell phytoliths (1200 BC) - SEM

2.4. Preservation of phytoliths

Preservation of phytoliths in soil depends on its chemical attributes. Phytoliths are reported to be invariable in both aerobic and anaerobic soil. The formation of silicate ions above pH 9 increases the solubility of silica. (Jones and Handrrek, 1967), young phytoliths susceptible to disintegration process than older forms (Bartoli and Wilding 1980). Deposition of silica to the biomass is known to increase with temperature. Presence of organic matter in the sediments could reduce the solubility of silica (Siever, 1972). Phytolith preservations have been found in Lake cores (Piperno 1985) ocean cores and periglacial sediments (Fredund et al., 1985).

2.5. Functional significance of phytoliths

Mechanical support and resistance to herbivore and pathogenic fungi are few of the cited functions of phytoliths in general. Phytoliths in grasses show resistance to perdition by mammalian herbivore and chewing insects. Phytoliths in plants are also known to be compression-resisting elements, which prevent collapse of cell walls during transpiration (Rovenr, 1983), and delay wilting of leaves (Postek, 1981). Phytoliths in plants act as 'nutrients' especially in plants like *Oryza*. Conditions of dryness in *Oryza* plants create supersaturation of soluble silica and cause its leaching. Thus, there is a constant requirement for silica in such plants (Cheng, 1982). At times they also function as micronutrients as they improve the growth response of plants (Jones and Handrek, 1967; Marchner, 1986).

3. Basic Phytolith Classification

The basic grouping/classification of phytoliths includes the taxonomic and the nontaxonomic system. Taxonomic classification is based on the comparison of phytolith shapes to the species that produce them with respect to the genus, tribe, subfamily and family. While in the non-taxonomic classification emphasizes the shapes of the silica bodies but are classified on a broad-based system, which include family, subfamily or the order to which they may belong to (Piperno, 1988).

The nomenclature of phytoliths, are based either on their shapes, their morphology or generic origin. They are also termed on the bases of their specific cellular origins in living tissues. Phytoliths are characterised by their shape, size, dimension, orientation and ornamentation.

3.1. Category of Phytoliths

The major types of phytoliths produced by plant tissues and cells are as follows;

3.2. Epidermal phytolits:

The epidermis forms a continues layer over the surface of the plants. These cells are generally silicified resulting in shapes that are identical between wide ranges of taxa. The epidermal phytoliths can be classified into two types, namely the with a wavy or polyhedral margin (square to rectangular) and the other with four to eight sides with square to rectangular appearance. The epidermal phytoliths formed in monocotyledons are of various forms that are derived from idioblast cells. These are located over the veins of leaf epidermis such phytoliths are the short cell phytoliths e.g. dumbbell (bilobates), cross shaped, circular, trapezoids etc (Piperno, 1988).

Hair cells on the leaf epidermis serve as a protective cover, these silicified hairs are often with a triangular apex with a spherical , elliptical or flat base. Such hair cells are primarily found in dicotyledons and also in certain monocotyledons like the gramineae.

3.3. Mesophyll Phytoliths

Mesophyll is the ground tissue of the leaf within epidermis specialised as a photosynthetic tissue. Palisade mesophyll consists of silicified elongated cells arranged in rows and the spongy mesophyll cells have a regular appearance. The mesophyll produces a number of phytolith shapes; conical, 'hat' shaped, 'fan' shape (Bulliform), spherical to aspherical and various irregular shapes that are taxonomically significant. Bulliform cells occur in longitudinal rows in the leaf epidermis of certain grasses. They are present on the dorsal side of the leaf running parallel to the veins. The bulliform silica cells have thick outer walls and are also cutinised like other epidermal cells.

3.4. Schlerenchyma Phytoliths

The schlerenchyma cells are known to be the strengthening elements of the mature plants, with a thick lignified cell wall. They are of two types, elongate fibers and schlerids of various shapes.

3.5. Vascular tissue

The xylem and phloem of vascular tissue show silicification. The water conducting tracheids produce elongate silicified bodies with irregular outline.

3.6. Phytolith surface ornamentation

The surface ornamentation of the phytoliths are defined as, spinoluse, nodular, regular, smooth, irregularly angled, verrucose, tuberculate, stippled, armed and nonarmed. Of which spinoluse, nodular and irregularly shaped occur rarely in monocotyledons. Sipnulose surface ornamentation has small projections regularly and unevenly distributed on the phytolith surface. Nodular phytoliths have a surface with small projections with uneven distribution, they are generally found on the conical and spherical phytoliths. The rugulose is defined as a rough surface pattern in which spinoluse and nodules are not clearly evident. Such phytoliths generally occur in seeds and leafs. Smooth surface refers to phytoliths with no pattern on their surface. Wart-like verrucose and tuberculate patterns are found on the surface of specialized phytoliths known as Cystoliths. Although such descriptive methods are still in use, a recent key has been proposed by Bowdery et al. (2001) for more scientific understanding of the surface ornamentation.

4. Phytolith Classification by Twiss et al. (1969,1988)

The Phytolith classifications used today are mostly based on the work of Metchalf (1960, 1971). Further work by Twiss *et al.* (1969, 1986) stands out to be the most frequently used classification today by the analysts. This nontaxanomic classification correlates four major short cell shape of grass leave i.e. bilobates, crosses, saddle and circular to acicular with three subfamilies namely the Panicoideae, Chloridoideae and Festucoideae.

4.1. Class I : Festucoid

Contains circular, rectangular, elliptical, crescent or oblong phytoliths. These phytoliths characterize the subfamily Festucoideae, which use the C_3 pathway or the Calvin-Benran cycle. The first fixed carbon compounds in this cycle consist of three carbon atoms.

4.2. Class II Chloridoid

Contains two type of saddle shaped phytoliths. This class contains grasses of the subfamily Eragrostideae, which are C_4 plants.

4.3. Class III Panicoid

Contain about 11 types of phytoliths types. The class occurs in the subfamily panicoideae, which include both C_3 and C_4 plants.

These three subfamilies are termed as "regular" in which the other forms can be added such as elongates, fan shaped (bulliform cells), point shaped and other unidentified phytolith fragments (Twiss, 1992). Further modifications have been made to accommodate changes in the higher level taxonomy of grasses in which there could be less correlation between phytolith shapes and grass taxonomy. Based on this, other subfamilies of grass could be recognised.

5. History of phytolith Research

The history of phytolith research can be divided into four phases of development.

5.1. Phase One: The discovery and exploratory stage from 1835 to 1900.

During this phase phytoliths (silica bodies) were initially isolated, observed and named. In the early phase of the nineteenth century pioneering research was conducted by Struve a German Botanist in 1835, he observed phytoliths from living plants. Charles Darwin in 1831 collected few dust samples during his expedition on H.M.S. Beagle. These samples were analysed by Professor Ehrenberg a German scientist. He classified and recognised several phytolith morphotypes from these samples and called them "Phytolitheria" (meaning "Plant stone" in Greek language) and developed the first classification system of phytoliths (Piperno, 1988).

5.2. Phase Two: The botanical Phase 1900 to 1936

Most of the research was conducted in Germany during which major emphasis was given on phytoliths from plant tissues. The production of phytolith types, their morphology and taxonomy. It was in this phase that Netalizky conducted phytolith analysis on grasses from archaeological sites in 1929.

5.3. Phase Three: The Ecological Phytolith Research. Mid 50's to 1975.

Table 1. Selected chronology of Phytolith research from c.1835 to 1980's

Year	Author/s	Phytoliths studied from/in	Remarks
1835	Struver	Living plants	Pioneering work
1841 1846 1854	Ehrenberg	Soil samples	Samples from H.M.S Beagel collected by Charles Darwin. Developed 1st classification system, the 'Parataxanomic' system. *Coined the term 'Phytolithera'
1855	Gegory	Plants and soil	Emphasised on morphology and location of silica cells.
1875	Hohnel	*Panicum miliaceum* (common millet), *Sorghum vulgare* (sorghum), *Avena sativa* (oat) *Triticum spelta* (spelt wheat) *Hordeum vulgare* (six rowed barley) *Secale cereale* (rye)	Detailed discussion on morphology of epidermal cells, prickle hair and bristle hairs
1896	Grob	Many plant families including monoctyledon, dicotyledons and fern.	Emphasised on morphology and location of silica cells.
1886	Guntz	130 species of grasses; bamboo, savannah, Medow and steppee grass.	Emphasised on morphology and location of silica cells, especially from leaf structures.
1899	Formanek	*Oryza sativa, Hordeum,Lolium temulentum, Avena fatua, Avena sativa, Panicum miliaceum, Triticum repens, Setaria viridus, Triticum repens.*	Studied silicification of grass family
1908	Mobius	*Chrysobalanaceae, Dilleniaceae, Palme, Orchidaceae, Urticaceae, Hymenophyllaceae* and a fern genus *Trichomanes.*	Studied silicification of grass family
1929	Netolitzhy	Podostemaceae, Chrysabalanaceae, Burseraceae, Palme, Musaceae, Cannaceae	Studied silicification of grass family
1936	Leeper, Nichollos and Wadham	Minerological sediments	Studied silicification of grass family
1937	Tyuria	Soil sediments	

Year	Author/s	Phytoliths studied from/in	Remarks
1956	Usov	Soil sediments	
1956	Parfenova	Soil sediments	
1956	Yarilova	Soil sediments	
1960	Metcalf	*Gramineae*	classified silica types on the basis of grass families; Chloridoid, Festucoid, Panicoid.
1969	Sangster and Parry	*Oryza sativa, Cynodon dactylon, Sieglingia decumbens*	Studied bulliforms by plant culture and light microscope
1970	Sangster	*Oryza sativa, Cynodon dactylon and Sieglingia decumbens*	Studied leaves by plant culture and light microscope
1973	Soni and Parry	*Oryza sativa* Linn.	Studied inflorescence bracts by electron probe micro analysis.
1977	Parry and Kelso	Saccharum officinarium	Studied roots using scanning electron microscope, electron probe micro analysis and Corinth analytical microscope
1981	Wadham and Parry	*Oryza sativa* Linn.	Studied culms, bracts and awns using scanning electron microscope, electron probe micro analysis
1982	Bennett	H*ordeum sativum, Avena sativa* and *Triticum avestium*	Studied roots using electron probe micro analysis
1986	Hodson and Parry	*Phalaris canariensis*	Studied roots, culm and leaves by plant culture using light microscope, scanning electron microscope and electron probe micro analysis.

It was in this period when an interdisciplinary work was undertaken by botanist, soil scientist, agronomist and geologist who applied phytolith analysis as an index of environmental history.

5.4. Phase Four: The Modern Phase.

The modern period of archaeological phytolith history began when systematic investigation into phytolith production and morphology in modern plants and phytoliths from archaeological and geological sediments.

6. Review of Phytolith Research in South Asia, Western World and East Asia(Korea region)

6.1. Phytolith research in India

Hardly any work has been conducted on Phytoliths from archaeological context in India; save Chowdhury and Ghosh (1954) who identified silica bodies of *Saccharum* sp. from the mud plaster found at the Proto-Historic site of Hastinapura (Period II c. 1100 BC to c. 800 BC). Besides this, there is another paper on Phytolith studies for interpreting shore environments in India by Mathur (1984). While the work by Kajale et al. (1995) gives an idea on the potential applications of Phytolith analysis for studying archaeological and quaternary problems in India. In recent years Kajale and Eksambekar (1997, 2001) have carried out some work on Chalcolithic and Neolithic sites in India.

Most of the Indian works on Phytoliths rather plant Silica bodies come from the botanical literature. Anatomist have specifically used the term 'Silica Bodies' (e.g. Ponnaiya, 1951; Sharma, 1965), while some analyst in recent times have used the term 'Phytolith' (e.g. Krishnan, 2001). Such information and the work conducted by various botanists are presented in a chronological order (Table 1). Most of the data is excerpted from Kajale et al. (1995) with some additions.

6.2. Phytolith Research in the Western World

Brief information on the researchers and their work in the history of phytolith research is presented in a tabular form (Table 2). The compilation includes the period from 1835 to 1980's excerpted from the from the review articles by Piperno (1988), Pearsall (1989) and Powers (1992) with some additions.

6.3. Phytolith Research in Korea

The environment for survival of organic remains is poor in most of korea, making the recovery of pollens and seeds unlikely in most cases. To the best of our knowledge phytolith analysis is a new technique in Korea however, we find significant research in 1970's by Fujihara who conducted phytolith analysis to understand Korea's earliest agriculture. In 1980's Kim and coworkers especially investigated phytoliths from Mumun pottery of Kumgokdong archaeological site (3580 BC approximate), here phytolits of rice and other crops like sorghum, millet and reed were identified. The botanical aspects of phytoliths were studies and highlighted by Kim and Whang (1992). Whang (1993) has made an outstanding contribution to understand the phytolith morphology of Oryza. Morphology of rice phytoliths was studies by Whang and Kim (1994) using Scanning Electron Microscope and distinctive phytoliths were noted from different parts of the plant. In most recent studies rice phytoliths have been recovered from Nongsori and Kumgokdong archaeological sites (Kwak, 1995). Environmental effects on phytolith morphology were studied by Wang et al. (1996) from rice cultivar of Korea and other counties. Gyoung-Ah (2000) has also contributed to phytolith analysis in Korean archaeology.

7. Research Applications

It can be seen from the above note how phytolith research has matured over time since 1835 to recent

Table 2. Review of Phytolith/silica bodies Research in India.

Year	Author	Silica bodies/phytoliths studied from	Investigation of /Remarks
1951	Ponnaiya	*Sorgum* sp.	Epidermal silica
1965	Sharma	Sedges	Conical silica bodies
1968	Govindrajul	*Eleocharis* sp., *Rhyncospora* sp. and *Scleria* sp.	Anatomical investigation
1970	Sharma and Rao	Timber species	Size form and distribution of silica
1970	Soni *et al.*	Oat plant	Anatomical investigations of leaf epidermis
1972	Sharma	*Scirpus squarrosus*	Anatomical investigation
1972a	Soni *et al.*	*Oryza sativa* L.	Anatomical investigation using Electron microprobe analysis
1972b	Soni and Parry	*Oryza sativa* L.	Anatomical investigation of inflorescence bracts using Electron microprobe analysis
1973a	Daynand and Kaufmann	Leaf epidermis	Guard cell using SEM
1973b	Daynand and Kaufmann	*Equisetum*	Guard cell using SEM
1977	Singh and Pande	Leaf epidermis	Stomatal types
1978	Srivastava	*Digitaria*	Morphology and location of silica bodies
1983	Dayanand *et al.*	Silica in Plants	Anatomical investigation
1999	Eksambekar *et al.*	Archaeological sediments	Surface ornamentation SEM
2000	Krishnan *et al.*	*Gramineae* sp.	Anatomical investigation. * Used the term ' Phytolith'

times. Phytolith applications are numerous and fourfold as they are capable of providing an independent avenue of data and interpretation to major areas of archaeobotanical studies like the origin and dispersal of domesticated and wild plants, development of agriculture, nature of paleoenvironment and its relation between technology, economy and social organization. Thus a few important areas of application are highlighted here;

7.1. Paleodiet

Armitage (1975) had conducted initial studies on phytoliths from herbivore dental calculus and reported some diagnostic phytolith forms.

Fox et al. (1996) identified phytoliths on the dental calculus of a human skeleton found at Lake Roman necropolis (Spain) they confirmed the presence of Poaceae phytoliths. These observations were undertaken using Scanning Electron Microscope and X-ray microanalysis. Here they also studied few soil samples from the abdominal area of the skeleton. They detected phytoliths belonged to Poaceae, Leguminoceae, Cyperaceae and Chenopodiaceae. These results were concordant with archaeological and ecological data.

Similar work has also been conducted on Herbivore dental calculus by Middleton (1990) to reconstruct prehistoric herbivore diet. The specimens were recovered from 18th century Hampsted, Virgina. The results gave an evidence of dominating Festucoid and Panicoid phytoliths in their diet.

7.2. Crop identfication and Agriculture

Fujuwara et al. (1992) reported the evidence of rice (*Oryza sativa* L.) and finger millet (*Eleusine coracana*) from Harappa (Indus valley). They extracted phytoliths from potsherds, terracotta objects, baked bricks, soil and ash.

Phytolith were analysed from occupational layers at the site of Kot-Diji Pakistan by Medalla (1995). The morphological investigations of phytoliths were used to detect two important crops of Sindh economy namely the *Sirkee* (in sindhi) *Saccharum bengalense* Retz. and Date Palm *Phoneix dactilifera* Linn.

Researchers like Pearsall et al. (1995) have attempted to differentiate wild rice from domestic rice. Their results suggest that the Oryza contribute phytoliths that are genus specific and the bulliform types alone do not help in separating the wild rice from the domestic variants. This method has helped archaeologist to identify domestic rice in archaeological context.

Based on comparative study Bamboo phytoliths were discovered by Hoyuyan et al. (1995) from a Loess Plateau in South China (7000-3000 B.P.). The study was in comparison with modern phytoliths from *Bambosoideae* sub families.

Phytolith analysis at Khok Phanom Di, a 4000 years old site in Bang Pokong valley has given evidence of rice agriculture and few grass weeds (Kealhofer and Piperno, 1994). The analysis was especially focused on the glume phytoliths of Oryza.

7.3. Paleoclimate

Alexander et al. (1997) recovered phytoliths from lacustrine sediments of lakes Guiers and Sinnda (Africa). The analysis resulted in understanding the Holocene History in comparison with pollen data. The phytolith sequences indicated grassland evolution around 2000 B.P. and semiarid humid grassland between 4000 and 1000 years B.P.

Similarly a comparative study was undertaken by Naiqin et al. (1995). They compared phytoliths from modern soil sample with the stratigraphic samples from a loess paleosol (at Weinan) to confirm the paleo climate around 30,000 B.P. The phytolith analysis indicated environments of cold, hot and cold types.

7.4. Phytolith morphometry and archaeobotanical records

Recent studies suggest that deviations in phytolith assemblages were caused by various botanical and environmental factors. Phytolith assemblages from leaf side, leaf position and individual plant of Maize (*Zea Mays* L.) were analysed by Mulholland *et al.* (1987,1990). Statistical analysis proved that singles sample is not sufficient for compilation of representative phytolith assemblages from a plant population. Multiple sampling is necessary to understand assemblage variation, as different leaf parts significantly affect phytolith assemblages.

Similar studies on wheat (*Triticum monocuccum*) were undertaken by Ball et al. (1993). Computer assisted image analysis indicated that inflorence bract, laminae and culms vary both taphonomically and morphometrically . Their analysis confirms that sampling of single plant part may not be representative of morphometric phytolith types.

Tubb et al. (1993) undertook a critical analysis of phytoliths from genera *Hordeum, Triticum* and *Aegilops*. They used light and scanning electron microscope and found variations in the diameter of silicified inflorsence papillae and a number of pits in the base of papilla. This helped in differentiating T. *avestum* from H. *vulgare* by taking into consideration the number of pits on the base of its silicified papilla. These characteristic anatomical features were useful in differentiating phytoliths from archaeological context.

Morphometic studies on the of leaf veins of 17 species of Oryza have been studied by Whang *et.al.*(1998). They used scanning electron microscopic backscatter images for analysis to find variation in silica bodies. Even within a single leaf blade the silica bodies were not uniform either on the midrib or veins. These factors confirmed the relation of water conducting systems and their influence on silica viability and phytolith formation.

8. Perspective

It can be seen that phytolith analysis has a wide scope of applications in archaeology and geo-archaeology as well as quaternary studies. The 1.8-1.6 million years of the Quaternary represents the time during which recognizable humans existed. Phytoliths are known to survive for longer period as compared to Pollens, spores and microfossils. With Phytolith analysis we can understand the paleoclimate and paleoenvironment and reconstruct the vegetation history at large. The Phytoliths are also good indicators of ecological changes at micro and macro levels. They also help us understand the land-use pattern, man-land relationship and flora of the area. Looking at the wide range of research application areas it can be said that Phytolith research has a potential scope in the "Korean geosciences" specifically aiming at the study of cores from wetland, fluvial and lake sediments. The application of such research will throw further light on the paleoenvironmental, paleoclimatological and 'site formation' processes in the Korean region.

References

Alexander, A., J.D. Meunier, A.M. Lezine, A. Vincens and D. Schwartz, 1997, Phytoliths: Indicators of Grassland Dynamics During Late Holocene in Intertropical Africa. Palaeogeography, Palaeoclimatology, Palaeocology, 136, 213-229.

Armitage, P. L., 1975, The Extraction and Identification of Opal Phytoliths from the Teeth Ungulates. Journal of Archaeological Science, 2, 187-197.

Ball, T.B., J. D. Brotherson and J. S. Gardner, 1993, A Typologic and Morphometric study of Variation in Phytoliths from Einkorn Wheat (*Triticum monococcum* L.). Canadian Journal of Botany, 71, 1182-1192.

Bartoli, F. and Wilding, 1980, Dissolution of Biogenic Opal as a Function of its Physical and Chemical Properties. Journal of Soil Science Society of America, 44(4), 873-878.

Bowdery, D., 1998, Phytolith Analysis to Pleistocene-Holocene Archaeological Sites in the Australian Arid Zone. BAR International Series 695. British Archaeological Reports, Oxford.

Bowdery, D., D. M.Hart, C. Lentfer and L. A.Wallis, 2001, A Universal Phytolith Key. In Phytolith: Applications in Earth Science and Human History.

(J.D. Meunier and F. Colin Eds.). A.A. Balkema Publishers, Lisse, p. 267-278.

Cheng, B.T., 1982, Some Significant Functions of Silicon to Higher Plants. Journal of Plant Nutrition, 5, 345-353.

Chowdhury, K.A. and S.S. Ghosh, 1954, Plant Remains from Hastinapura. Ancient India, 10, 120-137.

Eksambekar, S.P., S.R. Sainkar. and M.D. Kajale, 1999, Phytolith Studies Using Scanning Electron Microscope (SEM): Some Initial Considerations, Bulletin of Deccan College Post-Graduate and Research Institute, 58-59, 85-92.

Fox, C.A, J.Juan and R.M. Albert 1996, Phytoliyh Analysis on Dental Calculus, Enamel Surface And Burial Soil: Information About Diet and Paleoenvironment. American Journal of Physical Anthropology, 101, 101-113.

Fredlund, G.G., W.C. Johnson and W. Dort Jr. 1985, A preliminary Analysis of phytolith from the Eustic Ash Pit; Frontier Country, Nebraska, TER-QUA Symposium Series 1, 147-162.

Fujiwara, H., M. R. Mughal, A. Sasaki and T. Matano 1992, Rice and Ragi at Harappa: Preliminary Results by Plant Opal Analysis, Pakistan Archaeology, 27, 129-142.

Fujihara K. 1976, The Transition from Jomon to Yayoi as seen through plant opals. History Journal, 1, 63-70. (In Japanese)

Gyoung-Ah Lee, 2000, Recovery methods of plant remains and phytolith analysis in archaeology (in Korean). In The Origin of Prehistoric Rice Agriculture in Korea. H.J. Im (ed.), pp.132-145. Hakyeun, Seoul.

Houyuan, L., W. Naiquin, and N. Gaozhong, 1995, Discovery of Bamboo in the Loess-Paleosol Sequences of Guanzhong Basin, Shaanxi Province, Chinese Science Bulletin, 40(5), 405-409.

Jones, L.H.P. and K.A. Handreck, 1967, Silica in Soils, Plants and Animals, Advances in Agronomy, 19, 107-149.

Kajale, M.D., Susan Mulholland and George Rapp jr., 1995, Applications of Phytolith Analysis: a Potential Tool for Quaternary Environmental and Archaeological Investigations in the Indian Subcontinent, Memoirs Geological Society of India, 32, 530-544.

Kajale, M.D. and S. P. Eksambekar, 1997, Application of Phytolith Analyses to a Neolithic site at Budihal, district Gulbarga, South India, In Centro de Ciencias Medioambientales, CSIC, Monografias, Madrid. 4, 219-229.

Kajale, M.D. and S. P. Eksambekar 2001. Phytolith approach for Investigating ancient Occupations at Balathal, Rajasthan, India. Part 1: Evidence of Crops Exploited by Initial Farmers. pp. 199-204. Part 2: Late Chalcolithic to Earlihistoric Stratigraphic Reconstruction. pp. 205-212. In *Phytoliths:* Application in Earth Science and Human History. (J.E. Meunier and F. Colin Eds.) A.A. Balkema Publishers, Lisse.

Kealhofer, L and D.R. Piperno, 1994, Early agriculture in Southeast Asia : Phytolith Evidence from the Bang Pakong Valley, Thiland, Antiquity, 68, 564-572.

Kim and Chung, 1980, Kumgokdong Rock Shelter and Shell Mound. Pusan University Museum. (In Korean)

Kim, K.S. and Whang, S.S. 1992, Titles Nature of phytoliths and their applications in Botany(Chonbuk National Univ., Chonju (Korea Republic). Dept. of Biology)

Krishnan S., N. P. Samson, P. Ravichandran, D. Narasimhan and P. Dayanandan, 2000, Phytoliths of Indian Grasses and their Potential Use in Identification, Botanical Journal of the Linnean society, 132(3), 241-252.

Labouriau, L.G., 1983, Phytolith Work in Brazil, a Mini Review, The phytolitharien Newsletter, 2, 6-11.

Madella, M., 1995, A Preliminary Study of Phytolith Analysis, Agriculture and use of Plants at Kot Diji (Sindh- Pakistan), Ancient Sindh, 2, 93-108.

Marchner, H., 1986, Mineral nutrition of higher plants. Academic Press, London.

Mathur, K., 1984, Phytolitherians from the Bassein

Structure, Bombay Offshore, India, Proceedings of the Indian Colloquium on Micropalaeontology and stratigraphy, 10, 501-504.

Metcalfe, C.R., 1960, Anatomy of Monocyteledons I. Clarendon Press, Oxford.

Metcalfe, C.R., 1971, Anatomy of Monocyteledons V. Clarendon Press, Oxford.

Middeleton, W., 1990, An Improved Method for Extraction of Opal Phytoliths from Tartar Residue on Herbivore Teeth, The phytolitherian Newsletter, 6(3), 2-5.

Mulholland, S.C., G. Rapp, Jr. and A.L. Ollendorf, 1987, Variation in Phytoliths from Corn Leaves, Canadian Journal of Botany, 66, 20001-2008.

Mulholland, S.C., 1989, Phytolith shape frequencies in North Dakota Grasses: A Comparison to General Patterns, Journal of Archaeological science, 16, 489-511.

Mulholland, S.C., G. Rapp Jr., A.L. Ollendorf and R. Regal, 1990, Variation of Phytolith Assemblages Within a Population of Corn (cv. Mandan Yellow Flour), Canadian Journal of Botany, 68, 1638-1645.

Naiqin, W., L. Houyuan, S. Xiangjun, G. Zhengtang, L. Jiaqi and H. Jiamao, 1995, Climatic Factor Transfer Function From Opal Phytolith and Its Application In Paleoclimate Reconstruction Of China Loess-Paleosol Sequence, Scientia Geologica, Supplementary Issue (1), 105-114.

Parry, D.W. and F. Simitson, 1964, Types of Opaline Silica Deposits in the Leaves of British Grasses, Annals of Botany 28: 165-9.

Parry, D.W. and F. Simitson, 1966, Opaline Silica in the Inflorescence of some British Grasses, Annals of Botany, 30, 525-28.

Pease, D.S and J.U. Anderson, 1969, Opal phytoliths in *Bouteloua eriopoda* Torr. Roots and soils, Proceedings Soil Science Society of America, 33, 321-322.

Pearsall, D.M., M.K. Trimble and R.A. Benfer, 1985, A Method for Quantifying Phytolith Assemblages in Comparative and Archaeological Contexts. Paper presented at the 2nd phytolith Research Workshop, Duluth, MN.

Persall, D.M., 1989, Paleoethnobotany, A Handbook of Procedures. Academic press, New York.

Piperno, D.R., 1985, Phytolith Taphonomy and Distributions in Archaeological Sediments from Panama, Journal of Archaeological Science, 12, 247-267.

Piperno, D.R., 1988, Phytolith Analysis, An archaeological and Geological Perspective. Academic press, London.

Postek, M.T., 1981, The Occurrence of Silica in the Leaves of *Mangolia grandiflora* L, Botanical Gazette, 142, 124-134.

Powers, A. H., 1992, Great Expectations: A Short Historical Review of European Phytolith Systematics. In Phytolith Systematics: Emerging Issues (G. Rapp and Jr. S.C. Mulholland Eds.) Advances in Archaeological and Museum Science, 1, 15-35.

Sangster, A.G., 1985, Silicon Distribution and Anatomy of the Grass Rhizomes with Special Reference to *Miscanthus sacchariflorus* (Maxim.) Hackel, Annals of Botany, 55, 621-34.

Siever, R., 1972, Solublelites of Compounds Which Control Concentrations in Natural Waters, In: Handbook of Geochemistry (Wedepohl Ed.), II/2, Springer-Verlog, Berlin.

Tubb, H.J., M.J. Hodson and C.G. Hodson, 1993, The Inflorescence Papillae of the Triticeae: a New Tool for Taxonomic and Archaeological Research, Annals of Botany, 72, 537-545.

Twiss, P. C, E. Suess and R.M. Smith 1969, Morphological Classification of Grass Phytoliths, Soil Science Society of America, Proceedings 33, 109-115.

Twiss, P.C., 1986, Morphology of Opal phytoliths in C_3 and C_4 Grasses. In, Plant Opal Phytolith Analysis in Archaeology and Paleoecology (I. Rovner Ed.): Proceedings of the 1984 Phytolith Research Workshop, North Carolina State University, Keligh. Occasional Papers of the Phytolitharien, 1, 4-11.

Twiss, P.C., 1992, Predicted World Distribution of C_3

and C_4 Grass Phytoliths. In Phytolith Systematics: Emerging Issues (G. Rapp Jr. and S.C. Mulholland Eds.). Advances in Archaeological and Museum Science, 1, 113-128.

Whang, S.S., K. Kim and W.M. Hess, 1998, Variation of Silica Bodies in Leaf Epidermal Long Cells Within and Among Seventeen Species of *Oryza* (Poaceae), American Journal of Botany, 85(4), 461-466.

Wilding, L.P., R.E. Brown and N. Holowaychuk, 1967, Accessibility and Properties of Occluded Carbon in Biogenic Opal, Soil Science, 103, 56-61.

Wang Cailin, Udatsu Tetsuro and Fujiwara Hiroshi, 1996, Effects Of Cultivated Environment On Phytolith Morphology In Rice Motor Cells (*Oryza sativa* L.). Presented partially on the 13th Japan Cultural Assets Academic Committee of Science (Tokyo Gakugei University), June, 1996. East Jiangsu Province Agricultural Academy of Science; now United Graduate School of Agricultural Sciences, Kagoshima University, Miyazaki, 889-21, Japan.

Whang, S. S., 1993, Phytolith morphology and its taxonomic signification in the genus *Oryza*. Ph.D dissertation, Chonbuk National University.