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Research paper

Towards producing pure phytolith concentrates from plants that are suitable for carbon isotopic analysis

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ABSTRACT

Phytoliths are micrometric particles of amorphous silica that form inside or between the cells of higher plant tissues throughout the life of a plant. Phytolith morphological assemblages extracted from sediments and buried soils are increasingly used as proxies of grassland diversity and tree cover density. When found in significant amounts in archeological sites they can be used for identifying food habits, cultural and agricultural practices. Phytoliths can contain small amounts of C occluded in their structure (phytC). It is generally assumed that the source of this phytC is atmospheric CO₂ that was fixed by the plant via photosynthesis. Isotopic analyses of phytoliths ($\delta^{13}\text{C}$, ^{14}C) were thus expected to inform respectively on the photosynthetic pathway or on the age of the mineralized host plants. However recent ^{14}C analyses of phytC from phytolith concentrates extracted from soils and harvested grasses yielded unexpected ^{14}C ages of several hundreds to kyr old. These ^{14}C phytC results raised the question of a possible source of refractory/old soil organic matter component taken up by roots, which can be attached or occluded in phytoliths. Simultaneously these results highlighted the need for setting standardized protocols leading to concentrates entirely devoid of organic residues, as well as for a robust method for checking phytolith purity. The goal of this work was thus to develop protocols for extracting phytoliths from plants, leading to 100% phytolith purity, as required for phytC analyses. Protocol 1 utilizes a multi-step process of dry ashing and acid digestion, while protocol 2 also uses acid digestion as well as a separate alkali immersion step which removes surface layers. Phytolith concentrate purity was gauged in a semi-quantitative fashion through the use of SEM-EDS analysis. This quality check for phytolith purity can reveal small C particulate contamination of phytolith concentrates that may considerably bias isotopic and quantitative analyses of phytC. Results indicate that the two protocols were able to entirely remove small C particulate contamination. Protocol 1 produced phytolith concentrates with well defined morphologies suitable for both morphological and isotopic analyses. However measurement of C yields showed that protocol 1 probably induced C leakage, leading to lower recovery. Protocol 2 is faster, leads to higher C yield but may lead to a beginning of dissolution. With these protocols on hand, sources of phytC can be properly investigated.

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1. Introduction

Phytoliths are micrometric particles of amorphous silica (ASi) that form inside or between the cells of higher plant tissues throughout the life of a plant. Silicon (Si) is taken up by the roots in its dissolved form, translocated in the sap, and deposited in the cells where it can take the shape of the host cell. The concentration of phytoliths ranges from less than 0.01% of dry weight in many gymnosperms and dicotyledon angiosperms to more than 8% of dry weight in Poaceae,

Arecaceae, and Equisetaceae (e.g. Geis, 1973; Bozarth, 1992; Webb and Longstaffe, 2002). With plant decay, phytoliths that are preserved in oxidizing environments are either incorporated into soils or exported to sediments via regional watersheds. Phytolith morphological assemblages extracted from sediments and buried soils are increasingly used as proxies of grassland diversity and tree cover density (e.g. Blinnikov et al., 2002; Strömberg, 2002; Boyd et al., 2005; Bremond et al., 2005a, b; 2008a,b; Piperno, 2006; Lentfer and Torrence, 2007; Neumann et al., 2009; Messenger et al., 2010; Prasad et al., 2011). When found in significant amounts in archeological sites they can be used for identifying food habits, cultural and agricultural practices (e.g. Delhon et al., 2008; Li et al., 2010; Yost and Blinnikov, 2011). In parallel, phytoliths in plants, soils, and rivers were quantified for investigating the

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biogeochemical cycle of Si, which itself is coupled to the global C cycle (e.g. Blecker et al., 2006; Struyf et al., 2009; Alexandre et al., 2011; Cornelis et al., 2011).

Phytoliths can contain small amounts of C occluded in their structure (phytC), which is thought to range from 0.1 to 2% of phytolith dry weight (Wilding, 1967; Prychid et al., 2003). Raman spectroscopy and GC–MS analyses of phytC evidenced the presence of aliphatic compounds and lignins (Perry et al., 1987; Smith and Anderson, 2001), as well as aromatic hydrocarbon and graphite or coal when phytoliths were burnt (Pironon et al., 2001). PCR associated with protein staining detected the presence of glycoproteins but could not find evidence of any DNA (Elbaum et al., 2009).

It is generally assumed that the source of this phytC is atmospheric CO₂ that was fixed by the plant via photosynthesis (Wilding, 1967; Kelly et al., 1991; Raven et al., 1999; Piperno, 2006; Carter, 2009). From this basis, the assumption that phytC may be a terrestrial sink of C in the global C cycle was recently suggested (Parr and Sullivan, 2005; Jansson et al., 2010). In parallel, carbon isotopic studies have investigated the potential of phytC $\delta^{13}\text{C}$ signatures for providing information about photosynthetic pathways (Kelly et al., 1991; Smith and White, 2004; Webb and Longstaffe, 2010; Strömberg and McInerney, 2011) or deriving a paleo-atmospheric CO₂ record (Carter, 2009). However, isotopic calibration studies of phytoliths from grasses showed that the difference between $\delta^{13}\text{C}_{\text{tissue}}$ and $\delta^{13}\text{C}_{\text{phytC}}$ values is not constant from a plant to another (Smith and White, 2004; Webb and Longstaffe, 2010) and that changes in $\delta^{13}\text{C}_{\text{phytC}}$ values are not related to expected variation in the $\delta^{13}\text{C}$ values of atmospheric CO₂ (Webb and Longstaffe, 2010).

Few studies have used ¹⁴C ages of phytolith concentrates from soils and archeological sediments as chronological indicators (Piperno and Becker, 1996; Piperno and Stothert, 2003; McMichael et al., 2012). One of them found a modern or post-bomb age for phytolith concentrates

extracted from superficial soil (Piperno and Becker, 1996). Thousand-year ages were also reported for topsoil phytoliths (McMichael et al., 2012). This was justified by to the long mean residence time of phytoliths in soils. Other studies failed in matching ¹⁴C phytC values with expected or independent chronologies (Wilding, 1967; Kelly et al., 1991; McClaran and Umlauf, 2000; Prior et al., 2005; Rieser et al., 2007; Boaretto, 2009). Encountered difficulties were thought to be associated with stratigraphic inversions, preferential oxidation of younger phytoliths or mostly with ineffectiveness of phytolith extraction procedures (Wilding, 1967; Kelly et al., 1991; Prior et al., 2005; Rieser et al., 2007; Boaretto, 2009). Neither the phytolith chemical procedural blank assessment nor the reproducibility and accuracy checks on ¹⁴C of large pools of phytC were ever attempted to corroborate or explain the ¹⁴C results obtained. A recent study (Santos et al., 2010a) evaluated the background of phytolith chemical extractions and the reproducibility and accuracy of ¹⁴C phytC on phytolith concentrates extracted from soils and harvested grasses. Surprisingly, the phytC from harvested grasses yielded unexpected ¹⁴C ages of several kyr old (though bulk material from the same plants gave contemporary ¹⁴C values), when using an established protocol (Kelly, 1990; Kelly et al., 1991). This case is supported by phytC ¹⁴C-AMS data obtained from harvested bamboo leaves and underlying litter layers that were expected to reproduce contemporaneous atmospheric ¹⁴C values (Sullivan and Parr, 2008, 2013). As recently discussed in Santos et al. (2012a,b) the dataset shows varying depletions of at least 5 pMC (percent modern carbon) relative to the values expected when taking into account the southern hemisphere bomb radiocarbon peak and its recent decreasing trend in the atmosphere (Santos et al., 2012b). The minimum 5 pMC offset is equivalent to 400 years, reflecting incorporation of a substantial amount of “old” carbon in the phytolith concentrates (Santos et al., 2012b). The offset is maximum for the harvested leaves (which yielded an age of 3.5 ka BP), and undisturbed green litter with minimal contact

Table 1

Main steps of published protocols originally set up for phytolith extraction from plants. These protocols are commonly used for morphological identification purposes; some of them have been used for phytC analyses.

Protocols	Original references	Used for phytC analyses
Wet oxidation		
Main oxidizing agent: H₂SO₄/H₂O₂		
Rinsing of plant material with HCl. Boiling samples in 70% ethanol, washing and drying. Oxidation with concentrated H ₂ SO ₄ at 70°C. Addition of H ₂ O ₂ until solution is clear at room temperature. Rinsing with distilled water.	Geis, 1973, 1978 Kelly, 1990	Pironon et al., 2001 Smith and Anderson, 2001 Krull et al., 2003 Smith and White, 2004 Carter, 2009 Santos et al., 2010a Webb and Longstaffe, 2010
Main oxidizing agent: HNO₃/KClO₃		
Rinsing of plant material. Oxidation with concentrated HNO ₃ and KClO ₃ at 100°C. Removal of carbonates using HCl at room temperature. Rinsing with distilled water.	Rovner, 1972 Pearsall, 1989 Piperno, 2006	
Main oxidizing agent: HNO₃/HClO₄		
Rinsing of plant material with HCl. Two oxidation steps with a 1:1 HNO ₃ -HClO ₄ mixture at 80°C. Addition of H ₂ O ₂ at 80°C. Rinsing with distilled water.	Rovner, 1971	Elbaum et al., 2009 Santos et al., 2010a
Microwave digestion		
Oxidation with HNO ₃ , H ₂ O ₂ , and HCl in closed digestion tubes. Microwave irradiation for 30 min. Sieving at 250 μm Rinsing in ethanol	Parr et al., 2001b Parr, 2002	Krull et al., 2003 Parr et al., 2010 Parr and Sullivan, 2005, 2011
Ashing		
Rinsing of plant material with distilled water. Heating crucibles in muffle furnace at 500°C for 6h. Remove from crucibles to test tubes. Oxidation with HCl at 70°C for 20 min/rinsing. Oxidation with H ₂ O ₂ or HNO ₃ at 70°C for 20 min. Rinsing with distilled water.	Parr et al., 2001a	

with soil contaminants (1.8 ka BP). These ^{14}C results in addition to Santos et al.'s (2010a) findings raised the question of a possible source of refractory/old soil organic matter (SOM) component in soils taken up by roots, through nitrogen assimilation (amino acids or proteins) or in dissolved form (Santos et al., 2012a and references within), which can be attached to or occluded in phytoliths. Scanning Electron Microscope images coupled with Energy Dispersive Spectrometer analyses (SEM-EDS) from splits of the phytoliths of living grasses dated by Santos et al. (2010a) revealed the presence of particulate organic matter (OM) residues (Santos et al., 2012a) that may have contributed to bias in phytC ages. This fact emphasizes the need for setting standardized protocols for phytC analysis that can dissolve or oxidize all external organic remains.

Methods commonly used for extracting phytoliths from modern plant materials can be grouped into three categories: wet oxidation,

dry ashing and microwave digestion (Table 1). Although they were originally set up for phytolith morphological identification which does not require 100% purity, a survey of the published literature shows that some of them were used for plant phytC isotopic analyses (Table 1). Very few reports are available to evaluate phytolith concentrate purity (Parr et al., 2001a,b). This type of assessment is mostly performed by optical microscope evaluations, sometimes including cross-polarized light (Parr et al., 2010; Parr and Sullivan, 2011) which does not allow for the identification of non-polarizing organic remains (other than cellulose). FT-IR spectroscopy can be used on phytolith concentrates to check mineral purity (Cabanès et al., 2011), however, it has a low detection limit of organic compounds (1%).

Here we used SEM-EDS analyses to check for OM remains in phytolith concentrates. Moreover, we developed two protocols for extracting phytoliths from plants, leading to 100% phytolith purity, as required for

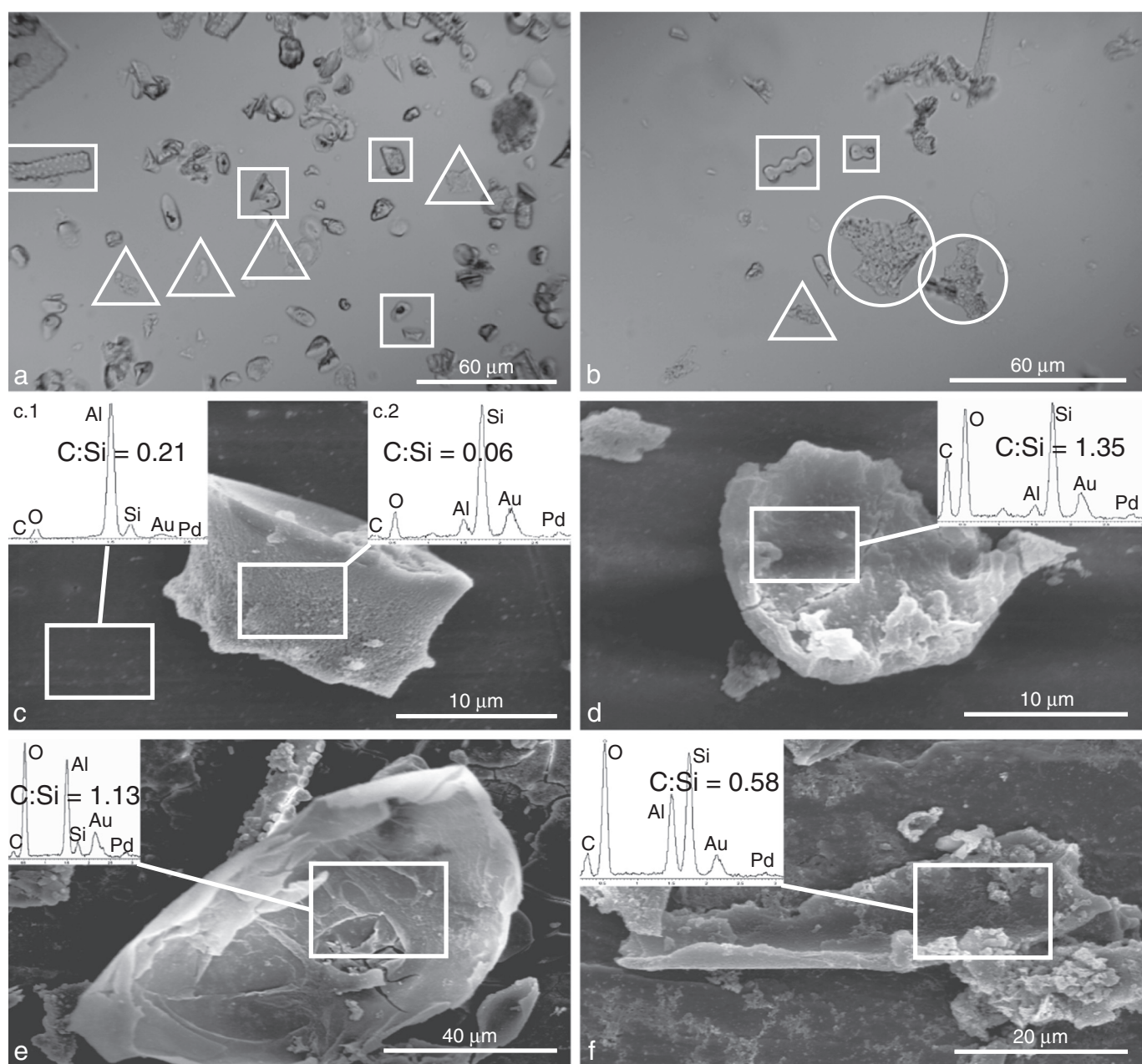


Fig. 1. Images of non-pure phytolith concentrates from Grass 1 and MN samples extracted following Kelly (1990). Optical microscopic images from (a) Grass 1, and (b) MN, showing highly refractive phytolith particles (white rectangles), poorly refractive particles without characteristic shape (white triangles) and tissue-like particles (white circles). SEM images and EDS spectra of (c.1) Al sample holder, (c.2) rondel type phytolith, (d), (e) and (f) organic particles. 1-c, 1-d and 1-e are reproduced from Santos et al. (2012a) for the purpose of the comparison between pure and non-pure phytolith concentrates.

Table 2

Two protocols of phytolith extraction from plants assessed at CEREGE and UWM as leading to pure phytolith concentrates.

Protocol 1—wet digestion/dry ashing	Protocol 2—wet digestion
(1) Dry sample at 110 °C for 24 h then cut into cm-sized pieces.	(1) Dry sample at 110 °C for 24 h then cut into cm-sized pieces.
(2) Grind samples.	(2) Place sample with DW* in ultrasonic bath to remove particulate matter from the surface.
(3) Place sample with DW* in ultrasonic bath for 15 min to remove particulate matter from the surface.	(3) Immerse in 10% HCl to remove any carbonates and agitate for 30 min. Rinse with DW 3 times.
(4) Place sample in a porcelain crucible and oven dry at 110 °C for 24 h.	(4) Place samples in glass beaker and add concentrated H ₂ SO ₄ . Allow to react for 2 h at 70 °C then allow to sit unheated overnight.
(5) Place the crucible in a muffle furnace and increase temperature incrementally from 300 °C to 500 °C (300 °C–325 °C–350 °C–375 °C–500 °C) over 4 h. Hold for 4 h at 500 °C.	(5) Reheat to 70 °C then slowly add 30% H ₂ O ₂ while stirring until the supernatant turns clear. Keep under heat for 2 h, stirring occasionally. Allow to sit, heated, for another hour. Pour off the supernatant then rinse the sample 3 times with DW.
(6) Place sample in a glass beaker and rinse/soak with 10% HCl for 30 min to remove any carbonates. Rinse with DW* 3 times.	(6) Add concentrated HNO ₃ and heat at 70 °C for 2 h. Add a pinch of KClO ₃ to facilitate digestion. Allow to sit unheated overnight. Decant then repeat this step to maximize organic matter oxidation. Rinse 3 times with DW.
(7) Add a 65% HNO ₃ /70% HClO ₄ mixture (2:1) and place on sand bath at 80 °C for 16 h.	(7) Immerse the phytoliths in 0.001 M KOH solution (pH = 11) and heat at 70 °C for 15 min to remove any alkali-soluble forms of OM*.
(8) Rinse with DW three times. Place sample in a porcelain crucible and oven dry at 110 °C for 24 h.	(8) Extract material using PP filters. Rinse with DW, transfer to glass vials then dry at 110 °C overnight.
(9) Repeat steps (5) and (7).	(9) Check purity by SEM/EDS.
(10) Add H ₂ O ₂ and place on sand bath at 80 °C for 16 h.	
(11) Rinse with DW 3 times.	
(12) Check purity by SEM/EDS. If some OM* still remains, repeat steps 2 to 6.	

* DW: distilled water; OM: organic matter.

phytC analyses. Regarding phytolith extraction from soils and sediments, we already have in hand a high purity protocol commonly used for phytolith oxygen isotopic analyses (Crespin et al., 2010; Alexandre et al., 2012).

2. Material and methods

Several combinations of the protocols listed in Table 1 were tested on random grasses of no relevance until consistently satisfactory results

were achieved. The two final protocols were applied to 50 g of leaves of harvested sorghum (*Sorghum bicolor*), in preparation for ulterior ¹⁴C-AMS analyses of phytC. The protocols were devoid of any organic chemicals that can sorb to the surface of clean silica (Schlechtriem et al., 2003; Santos et al., 2010a).

Final phytolith concentrates were observed under optical microscopy and analyzed using a SEM (Philips XL30) associated with an EDS system (Energy-dispersive X-ray spectroscopy, Oxford) according to the following steps: 1) coating with gold and palladium of the samples placed on

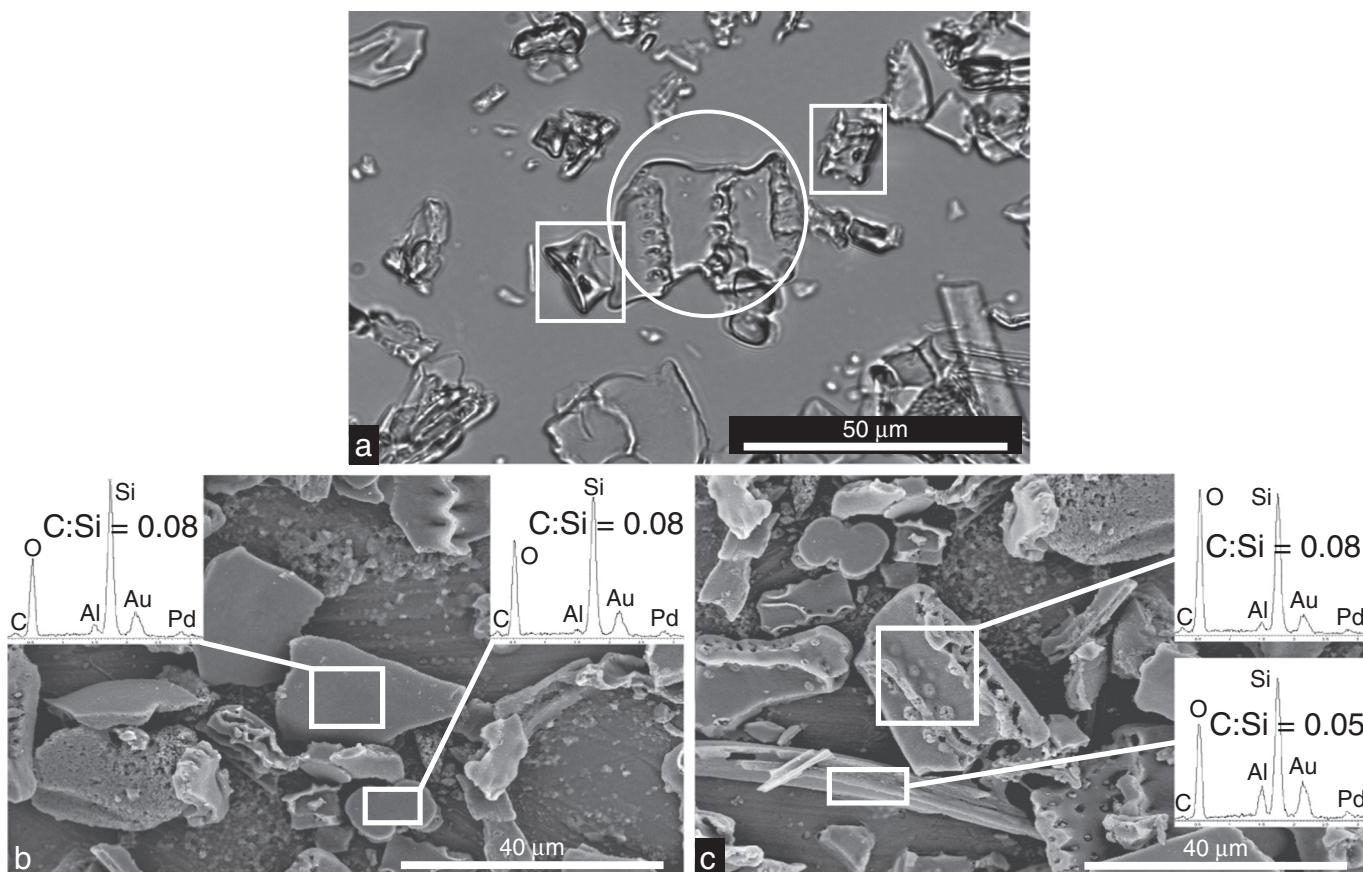


Fig. 2. (a) Optical microscopy images of phytoliths from *Sorghum bicolor* leaves, extracted following Protocol 1, showing highly refractive phytolith-like particles (white rectangles) and tissue-like particles (white circle). SEM images and EDS spectra of (b) phytoliths and (c) tissue-like particles.

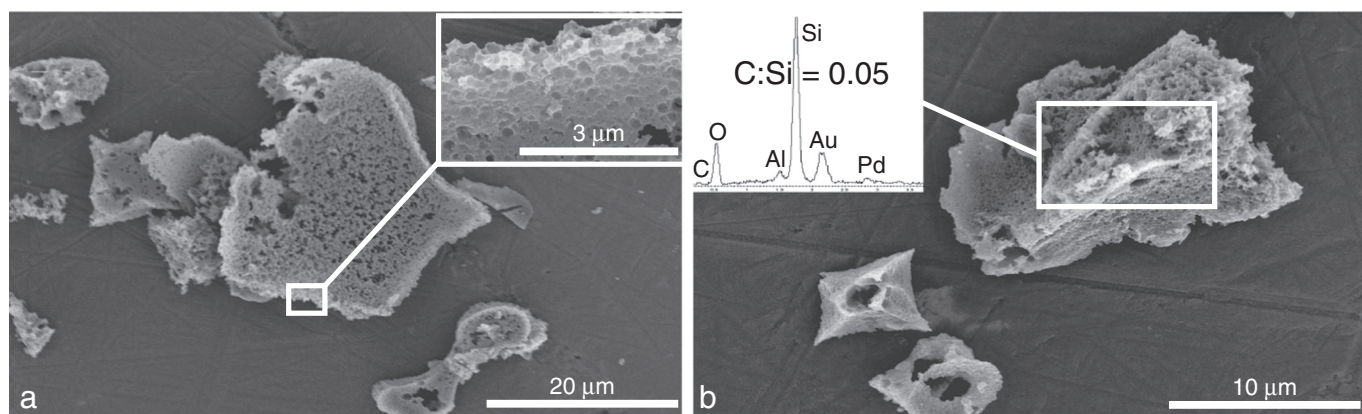


Fig. 3. (a) and (b) SEM images and EDS spectra of phytoliths particles from *Sorghum bicolor* leaves extracted following Protocol 2, including the use of KOH @ pH 13. Pits scattered on the phytolith surfaces evidence dissolution.

an Al holder; 2) SEM spotting of organic-like particles showing tissue-like or non-phytolith morphologies; 3) EDS semi-quantitative analyses of C, Si and Ca (indicative of the presence of C-bearing Ca-carbonates). Although SEM–EDS data are semi-quantitative and little accurate for C determination, C:Si % mass ratios, obtained from 10 to 30 µm spots were distinct enough to allow detection of silica particles and organic remains (Fig. 1).

For the purpose of comparison, two samples obtained by Santos and co-workers (Grass 1 and MN; Santos et al., 2010a) using the H₂SO₄/H₂O₂ protocol from which organic remains were previously evidenced (Santos et al., 2012a) were re-investigated using optical microscopy and SEM–EDS (Fig. 1).

In order to determine the carbon percentage of the phytC obtained by the optimized protocols, 100% pure phytolith concentrate samples were combusted at 900 °C in evacuated sealed 6 mm OD pre-baked quartz tubes in the presence of cupric oxide (Santos et al., 2010a), and the cryogenically cleaned CO₂ yield was measured manometrically at room temperature on a vacuum line (Santos et al., 2004).

3. Results and discussions

When observed in optical microscopy, non-pure phytolith concentrates obtained from Grass 1 and MN samples evidenced three categories of particles (Fig. 1): 1) highly refractive phytoliths; 2) poorly refractive particles without characteristic shape; and 3) tissue-like particles. SEM–EDS analyses (Fig. 1) allowed us to clearly categorize the observed particles into: 1) silica particles (or phytoliths) with values of C:Si % mass ratios equal or lower than values obtained for the Al sample holder (<0.5); 2) organic remains with values of C:Si % mass ratios higher than 0.5. Most of the tissue-like particles were silica (C:Si %

mass <0.5). Organic remains (C:Si % mass >0.5) were mainly unshaped particles. No Ca was found by EDS analysis.

After several trial experiments to refine phytolith extraction protocols, two protocols were finally kept. They are described in Table 2. Protocol 1 (Table 2) combines methods described in Rovner (1971), Parr et al. (2001a) and Piperno (2006). It includes multi-step wet oxidation using HNO₃ and HClO₄ along with dry ashing. Protocol 2 combines methods described in Geis (1973), Pearsall (1989), Prior et al. (2005) and Piperno (2006). It is a wet digestion using H₂O₂, HNO₃, KClO₃, and KOH, sometimes used for soil phytolith extraction (Piperno, 2006). Several tests were made with three concentrations of KOH (0.001 M @ pH 11; 0.01 M @ pH 12 and 0.1 M @ pH 13). Methodic checking for carbon particulate contamination, using SEM–EDS analysis, revealed the absence of Ca and only the presence of particles with C:Si peak area ratios lower than 0.1 (Figs. 2 and 3). Thus, both protocols led to phytolith concentrates pure enough for phytC isotopic analyses. Protocol 1 produced phytolith concentrates including tissue-like Si particles with well preserved ornamentation (Madella et al., 2005) (Fig. 2). Ornamentation features were well preserved when Protocol 2 included the use of KOH @ pH 11 and 12 but started dissolve when KOH was used @ pH 13 (Fig. 4).

The carbon yields of phytolith concentrates from protocols 1 and 2 were 0.053 and 0.21%, respectively, and were reproducible among duplicates. From SEM–EDS analyses and phytC CO₂ yields, we can conclude that both of these protocols show advantages and disadvantages: Protocol 1 produces phytoliths with preserved ornamentation excellent for morphological counting prior to phytC analyses. However repeated ashing up to 500 °C may lead to C leakage as evidenced by the low CO₂ yield measured herein. This necessitates that a large amount of phytoliths (ca. 800 mg) need to be extracted from plant material (ca. 800 g assuming a phytolith content of 0.1% dry weight of bulk plant tissue) for obtaining large graphite targets of ~0.4 mg of C. However several AMS

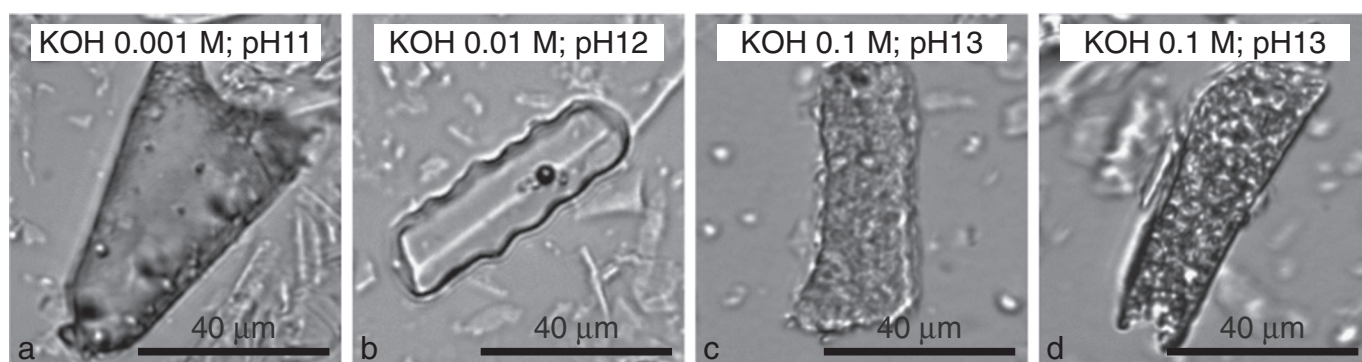


Fig. 4. Optical microscopy images of phytoliths obtained after Protocol 2 using three concentrations of KOH: (a) 0.001 M @ pH11; (b) 0.01 M @ pH 12; (c) and (d) 0.1 M @ pH 13. Pits scattered on the phytolith surfaces evidence dissolution @ pH 13.

facilities are today able to measure samples as small as 0.010 mg C with 1 sigma errors of just 1% on close-to-modern targets (Santos et al., 2007; de Rooij et al., 2010; Fahrni et al., 2010; Ruff et al., 2010) which brings the required amount of phytolith to ca. 20 mg (using protocol 1) or 5 mg (using protocol 2). However, one should note that ^{14}C -AMS samples produced from some chemical extractions bear higher blanks (Santos et al., 2010a, b), and therefore slightly larger amounts of biosilica concentrates in order to produce larger graphite samples are recommended. Another drawback of protocol 1 is the use of HClO_4 , which is dangerous to handle and requires the use of a specialized fume hood. Protocol 2, which does not utilize dry ashing, is faster and avoids the problem of C leakage. We were able to extract approximately four times more phytC with this approach, as compared to protocol 1. However the use of KOH concentrations above pH 12 should be avoided as it induces fast silica dissolution which needs to be carefully monitored. Finally, these protocols are both suitable for phytolith extraction prior to phytC isotopic analyses. The choice of one or another will depend on the amount of plant material, on available time and equipment, and on the amount of pure phytoliths required for accurate and reproducible analyses.

4. Conclusion

This study highlights the need of a robust method for checking phytolith purity prior to phytC quantification and isotopic analyses. SEM-EDS analysis of Ca, C and Si, although yielding semi-quantitative estimations, is suitable to be used as a routine method for phytolith concentrate purity evaluation. Organic remains, that may not be accounted for under light microscopy, can be clearly individualized from their high C:Si % mass ratios. This quality check for phytolith purity may reveal small C particulate contamination of phytolith concentrates that may considerably bias isotopic and quantitative analyses of phytC.

With the aim of phytC isotopic analyses, we have assessed two plant phytolith extraction protocols which yielded phytolith concentrates devoid of organic remains. Methodological advantages and drawbacks of both protocols were presented. With these protocols on hand, sources and concentration of phytC and possibly organic carbon involvement in biosilica synthesis of higher plants can be now properly investigated.

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