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1 **Confocal volumetric μ XRF and fluorescence computed**
2 **μ -tomography reveals arsenic three-dimensional distribution**
3 **within intact *Pteris vittata* fronds**

4
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31

32 **ABSTRACT**

33 The fern *Pteris vittata* has been the subject of numerous studies because its extreme arsenic
34 hyperaccumulation characteristics. However, information on the arsenic chemical speciation and
35 distribution across cell types within intact frozen-hydrated *Pteris vittata* fronds is necessary to better
36 understand the arsenic biotransformation pathways in this unusual fern. While 2D X-ray absorption
37 spectroscopy imaging studies show that different chemical forms of arsenic – As(III) and As(V) –
38 occur across the plant organs, depth-resolved information of arsenic distribution and chemical
39 speciation in different cell types within tissues of *Pteris vittata* have not been reported. By using a
40 combination of planar and confocal μ -X-ray fluorescence imaging and fluorescence computed μ -
41 tomography, this study reveals the localization of Arsenic in the endodermis and pericycle
42 surrounding the vascular bundles in the rachis and the pinnules of the fern. Arsenic is also
43 accumulated in the vascular bundles connecting into each sporangium, and in some mature sori. The
44 use of 2D X-ray absorption near edge structure imaging allows for deciphering arsenic speciation
45 across the tissues, revealing arsenate in the vascular bundles and arsenite in the endodermis and
46 pericycle. This study demonstrates how different advanced synchrotron X-ray microscopy
47 techniques can be complementary in revealing, at tissue and cellular levels, elemental distribution
48 and chemical speciation in hyperaccumulator plants.

49

50 **Keywords:** *chemical speciation; elemental distribution; hyperaccumulator; fern.*

51

52

53 1. INTRODUCTION

54 Hyperaccumulator plants are able to regulate potentially toxic concentrations of trace elements in
55 their living tissues^{1,2,3}. Arsenic hyperaccumulation has been described for a number of pteridophytes
56 (ferns) from the genus *Pteris* (Pteridaceae), most notably *Pteris vittata*, which accumulates up to
57 22 600 $\mu\text{g g}^{-1}$ As^{4,5} and *Pityrogramma calomelanos* which accumulates up to 16 400 $\mu\text{g g}^{-1}$ As^{6,7} in
58 fronds. Phytoextraction with *P. vittata* has been successfully applied in the remediation of soil and
59 groundwater As^{8,9,10}. The As hyperaccumulation mechanisms of *P. vittata* have elicited intensive
60 research^{11,12,13,14}. Arsenic content in *P. vittata* follows the order of pinnae > stipe > root, with most
61 As distributed in the pinnae (78–96%). The concentration of As in the pinnae decreases from the
62 base to the apex of the fronds, and As concentrations in midribs is much lower than in the pinnae¹⁵.
63 The As concentration was relatively high in the midrib compared to the surrounding tissues, and
64 there could be an unloading process of As from midrib to mesophyll tissues¹⁶. An interesting finding
65 is that As concentrations in spores were far lower than in the pinnae, indicating that *P. vittata* tends
66 to keep As away from reproductive organelles¹⁵. At the cellular level, energy dispersive X-ray
67 spectroscopy combined to scanning electron microscopy (SEM-EDS) identified that As is primarily
68 distributed within the upper and lower epidermis of the pinna in *P. vittata*¹⁵. Analysis with X-ray
69 fluorescence imaging (μXRF) led to the reporting of even higher As concentration in trichomes
70 compared that prevailing As concentrations in the epidermis¹⁷. At the subcellular level, As was
71 mainly stored in the cytoplasmic supernatant fraction, accounting for 78% of As in the pinnae¹⁸.
72 Therefore, As compartmentalisation in trichomes and vacuoles was suggested as a detoxification
73 mechanism in *P. vittata*^{15,17}. Recently, localization of As in the apoplast near the midrib, in fronds of
74 *P. vittata* was reported¹⁹. A similarity between the As and K distribution at both cellular and
75 subcellular level was found^{15,20}, implying that K^+ may act as a counterbalance to $\text{As}^{\text{V}}\text{O}_4^{3-}$ anions.

76
77 *Pteris vittata* contains As predominantly as inorganic As species²¹. Regardless of whether As(III) or
78 As(V) was supplied to the plants, the oxidized form As(V) dominated in the roots while As(III)
79 dominated in the rhizomes and fronds^{15,21,22,23,24,25}, suggesting that the reduction of As(V) to As(III)
80 occurs during As translocation. Furthermore, X-ray absorption spectroscopy indicated that, in the
81 pinnae, As(III) was predominantly coordinated with oxygen^{22,25}. The precise location where As(V) is
82 reduced to As(III) is still unknown. The reduction of As(V) to As(III) was firstly considered to occur
83 in the pinnae as it was found that As in xylem sap was mainly As(V)^{21,23}. It was proposed that As(V)
84 is transported through the vascular tissue from the roots to the fronds, where it is reduced to As(III)
85 and stored at high concentrations²⁵. As(V) is reduced mainly in roots and not in the fronds^{22,24} and
86 root extracts from the *P. vittata* were able to reduce As(V) to As(III)²⁶. The reduction of As mainly

87 occurs in the endodermis of roots²⁷. Arsenic is transported in the xylem sap of *P. vittata*
88 predominantly (93–98%) as As(III), regardless of whether As(V) or As(III) was supplied to the
89 plants, implying that the roots are the main site of As(V) reduction in *P. vittata*²⁹. Similar reduction
90 of another metalloid, antimony (Sb), from pentavalent Sb to trivalent Sb has been reported in the
91 roots of *P. vittata*³⁰. However although clearly As(V) is reduced most effectively in root endodermis
92 and then As(III) is transported most effectively in xylem, the identification of As(V) in other tissues
93 means that not all of it is reduced in the root and the As(III) tris-glutathione [As(SR)₃] form found in
94 the surroundings of the vasculature suggests that reduction can occur also outside the root²⁵.

95 Despite all the previously cited publications, no study to date has revealed the As-distribution at the
96 cellular-scale in the *P. vittata* fronds, and previous data has only shown planar views of As
97 (projected onto a 2D plane). As such no depth information is currently available and the *in situ* 3D
98 distribution of As needs to be investigated and confirm the 2D visualisation. It is possible that
99 observed differences in As speciation across tissues are due to spatial variations of As in different
100 cell types^{27,31}. Pickering *et al.*²⁵ examined both the gametophyte generation and the sporophyte
101 generation, and found discrete speckles of arsenate localized in parenchymal cells (possibly in
102 vacuoles) in the gametophytes. Another study on a related As-hyperaccumulating fern
103 (*Pityrogramma calomelanos*) by Kachenko *et al.*⁷ showed substantial tissue-level differentiation in
104 As accumulation but could not reveal As chemical speciation.

105
106 Conventional synchrotron (planar or 2D) μ XRF of plant leaves (whole leaves or cross sections) is a
107 projection of all elements in a sample. As such, a planar view of a plant leaf reveals the elements
108 contained in the adaxial and abaxial epidermis and mesophyll together in a 'compressed' projected
109 2D plane. Several methods are available for revealing the detailed 3D elemental distributions
110 relevant to complex biological samples. In this article we employ three complementary approaches to
111 access the 3D elemental distributions: mechanical sectioning to access the distributions within a
112 single plane, X-ray fluorescence μ -computed tomography (XFM- μ CT) to determine volumetric
113 distributions from a series of projection images without sample sectioning, and confocal imaging to
114 directly access elemental distributions within targeted regions within the specimen. Although we
115 describe these methods here, a more detailed comparison can be found in de Jonge & Vogt³² and van
116 der Ent *et al.*³³.

117
118 Confocal optics enable a direct-space approach to deliver 3D resolution. A confocal optic confines
119 the field of view of the energy-dispersive detector so that the signal derives from only a small portion

120 of the illuminated column^{34,35,36}. The probe volume is thereby reduced to a spheroid and elemental
121 distribution is mapped in three dimensions by scanning the specimen through the probe volume. The
122 use of confocal X-ray fluorescence methods for the investigation of biological samples has been
123 limited to date, probably due to the increased X-ray dose associated with the confocal geometry in
124 most situations³⁷. Such an approach was, however, successfully utilized to decipher the distribution
125 and chemical speciation of selenium in zebrafish larvae³⁸.

126

127 Another approach to obtain information on the internal elemental distribution in physically intact
128 samples is X-ray fluorescence μ -computed tomography (XFM- μ CT). This technique enables
129 reconstruction of 2D or 3D elemental data from a rotation series of projection images. For typical
130 measurement modalities, μ CT requires the measurement of projection images from multiples view
131 around a fixed rotation axis. In order to avoid issues with self-absorption and to simplify the
132 measurement, XFM- μ CT is limited to measurements of specimen that are relatively thin in the two
133 dimensions around the rotation axis, such as roots^{39,40}, stems and narrow leaves⁴¹ and seeds⁴²,
134 although μ CT laminography could be used in flatter objects such as leaves. The confocal approach is
135 more tolerant to self-absorption effects, and especially well-suited to measure depth profiles in
136 extended planar objects such as leaves. Further, the confocal measurement enables direct access to
137 small volumes within a specimen and so is amenable to direct and *in situ* spectroscopic (XANES)
138 measurements.

139

140 Self-absorption is a combination of two effects that reduce the quantitative nature of reconstructions
141 obtained by XFM- μ CT and affect the visualization of element distribution: the absorption of the
142 incident X-ray photons and the re-absorption of the fluorescent X-ray photons (in particular low-
143 energy photons) by the specimen (for a review see Vogt & de Jonge³²). Self-absorption is usually
144 dominated by the latter of these effects, and this in turn has a greater impact on the quantitative
145 determinations of the elements with low energy x-ray photons for K-shell emission this corresponds
146 to with lower-Z elements. Self-absorption places a practical upper limit on the specimen dimensions,
147 so that, for example, Ni can be mapped in hydrated biological samples up to ~ 800 μm thick with
148 reasonable accuracy ($K\alpha$ line at 7.47 keV), but this increases up to ~ 1500 μm for As ($K\alpha$ line at
149 10.54 keV) assuming a tolerable limit of 50% self-absorption.

150

151 X-ray fluorescence microscopy (XFM) beamlines also offer the unique ability to perform *in situ* X-
152 ray absorption spectroscopy (XAS) to obtain information on the chemical speciation of elements (As

153 in this case) in plant tissues without preparations and avoiding the possibility for artefacts resulting
154 from those preparations. Moreover, the use of confocal optics allows examination of As chemical
155 speciation at depth in distinct cell types within intact plant tissues and hence elucidation of the
156 spatially resolved chemical speciation and elemental distribution in physically intact samples without
157 the need for destructive sample preparation^{33,43}.

158

159 The complexity of As distribution and chemical speciation requires a range of different
160 methodological approaches to understand the 3D distribution at the cellular level and also for the
161 speciation. This study uses a combination of different synchrotron X-ray methodological approaches
162 to interrogate As distribution and chemical speciation in *Pteris vittata* tissues, which are summarised
163 in Table 1. To date, depth-resolved information has not been available, and this study aims not only
164 to unravel the As pathway in the As hyperaccumulating fern *Pteris vittata*, but also to demonstrate
165 how a set of advanced synchrotron X-ray microscopy techniques can be complementary in revealing,
166 at tissue and cellular levels, the distribution and chemical speciation of As in this hyperaccumulator
167 plant.

168

169 **2. MATERIALS AND METHODS**

170

171 **2.1 Cultivation and collection of plant tissues and soils**

172 Tissue samples were obtained in one of two ways. Cultured tissue samples were obtained from *P.*
173 *vittata* grown in soil at the University of Queensland. The potting mix was spiked with an As(V)
174 solution supplied as $\text{Na}_2\text{HAsO}_4 \cdot 7\text{H}_2\text{O}$ prior to transplanting (dose rate was 1000 mg kg^{-1} as As). The
175 plants were grown in a greenhouse for two months with an 11-hr daily photoperiod, a photon flux of
176 $>370 \mu\text{mol m}^{-2} \text{ s}^{-1}$, a day-night temperature range of 20–29°C and relative humidity of ~70%. Tissue
177 samples of *P. vittata* were also collected from a contaminated site in Shimen, Hunan Province in
178 south China. This site is heavily contaminated by As due to realgar ore smelting activities in the past
179 (N29°39'33.88" E111°2'43.1") with a soil As concentration of $313 \mu\text{g g}^{-1}$. The live plants, together
180 with the soil attached to the roots, were transported from Hunan to Beijing, and maintained in the
181 laboratory in Beijing. Tissue samples intended for synchrotron XFM analysis were excised with a
182 razor blade and immediately shock-frozen using the metal mirror freezing technique (in which the
183 sample is rapidly pressed against a block of solid copper cooled by at -196°C liquid N_2). The samples
184 were then wrapped in Al-foil and transported in a cryogenic container (at least -190°C) for storage
185 and transport. Samples were also freeze-dried in a freeze-dryer (LABCONCO FreeZone 6) starting at
186 -50°C until room temperature in 48 hours. Slow freeze-drying has been shown to avoid, or at least,

187 reduce elemental re-distribution and tissue shrinkage^{44,45} but may cause subcellular migration of
188 dissolved elements to the nearest solid surface. The influence of freeze-drying on element chemical
189 speciation is still contentious and depends on several factors such as the element itself, its chemical
190 speciation and initial oxidation state^{46,47}.

191

192 Some physical cross-sections were prepared from the cultivated *P. vittata* fronds. After shock
193 freezing (as described earlier), the samples were cryo-transferred on dry ice (-80°C) into the cryo-
194 chamber of the microtome (maintained at -30°C) and mounted on a plate by application of chilled (-
195 8°C) polypropylene glycol for physical support. The fronds were then cut to 30 µm sections using a
196 cooled blade (-20 °C), and the sections transferred to pre-cooled 1 mL cryo-containers and freeze-
197 dried.

198

199 **2.2 Plant tissue bulk analysis**

200 Plant tissue samples for bulk chemical analysis were gathered from the cultured ferns after two
201 months, and from the freeze-dried fern samples from China. The samples were dried at 70°C for five
202 days in a dehydrating oven, subsequently ground and a 200-mg fraction digested using 4 mL
203 concentrated nitric acid (70%) and 1 mL hydrogen peroxide (30%) in a digestion microwave oven
204 (Milestone Start D) for a 45-minute programme. After cooling, the sample was diluted to 30 mL with
205 TDI water. The aliquots were analysed on ICP-AES (Varian Vista Pro II) for P, Mg, Ca, K, S and
206 As.

207

208 **2.3 Histochemistry and bright field microscopy**

209 Frond samples were fixed in 3% glutaraldehyde (in PBS), sectioned with a vibratome (Leica
210 VT1000s) and stained with Toluidine Blue. The sections (20–40 µm thickness) were then examined
211 and photographed with bright field microscope (Nikon Diskovery Spinning Disk Confocal with
212 Andor Zyla 4.2 camera).

213

214 **2.4 Scanning Electron Microscopy with X-ray microanalysis (SEM-EDS)**

215 Freeze-dried leaf samples were sputter-coated with carbon (25 nm) and mounted on stubs. The
216 samples were then imaged with Scanning Electron Microscopy (SEM) with X-ray microanalysis
217 (Energy dispersive X ray spectroscopy or EDS) on a JEOL JSM-6610 instrument. Images were
218 obtained for 100–1000 x magnifications at 5–15 kV with lower accelerator energies for imaging with
219 secondary electrons only and higher accelerator energies for imaging using backscattered electrons.

220

221 2.5 X-ray fluorescence microscopy (XFM)

222 The X-ray fluorescence microscopy (XFM) beamline of the Australian Synchrotron employs an in-
223 vacuum undulator to produce a brilliant X-ray beam of 4.1–20 keV with a focus down to 1000 nm. A
224 Si(111) monochromator and a pair of Kirkpatrick-Baez (KB) mirrors deliver a monochromatic
225 focused incident beam onto the specimen⁴⁸. The P06 beamline of PETRA III (Deutsches Elektronen-
226 Synchrotron; DESY) is also equipped with Si(111) monochromator and KB mirrors⁴⁹ producing X-
227 ray beam of 5–23 keV with a focus down to 300 nm. Both beamlines are equipped with a Maia
228 detector consisting of a large detector array to maximize the detection of fluorescence signal. The
229 Maia detector allows for high overall count-rates and uses an annular detector geometry, where the
230 beam passes through the detector and strikes the sample at normal incidence^{50,51}. This geometry
231 enables a large solid angle (1.2 steradian) to maximize detected signal and reducing the dose and
232 potential damage to a specimen⁵². Maia is designed for event-mode data acquisition, where each
233 detected X-ray event is recorded, tagged by detector number in the array, position in the scan and
234 other metadata⁵³. This approach eliminates readout delays and enables short pixel times (typically
235 down to 0.1 ms) and large pixel counts to be achieved for high definition imaging (typically 10–100
236 M pixels). The confocal experiment used a custom-made polycapillary collimating optic (XOS, input
237 focal distance 2.5 mm, input field of view 10.0 μm , transmission efficiency optimized for 17.4 keV
238 radiation) fitted on a Vortex SDD detector (Hitachi Vortex EM-90, 80mm², minimum energy of 1.6
239 keV, energy resolution 120 eV, operated in 90-degree geometry). The experimental setup at the
240 XFM beamline the Australian Synchrotron, showing both the Maia detector and SDD detector with
241 confocal optic, is shown in Fig 1.

242

243 On the XFM beamline, the confocal μXRF and μXAS experiments used a polycapillary optic fitted
244 on the SDD detector allowing for a depth resolution (dz) of $\sim 10 \mu\text{m}$ (energy and hence element-
245 dependant), while the beam spot size using the KB mirrors was $\sim 2 \mu\text{m}$. The resolution of the
246 polycapillary optic limits the z -resolution (along beam axis) of confocal tomography, while the beam
247 spot size limits the x - y -resolution. Accordingly, samples can be raster imaged with an effective probe
248 volume probe of volume of $\sim 10 \times 2 \times 2 \mu\text{m}$. The scan was carried out in the x - z plane which samples
249 the two smallest dimension of the pinnule - a virtual section – so that the y -axis is not probed, with a
250 1 second per pixel dwell time. The confocal $\mu\text{-XRF}$ images were recorded using a beam incident
251 energy of 15.8 keV

252

253 The fluorescence 2D XANES imaging at the XFM beamline was performed on a portion of a frozen-
254 hydrated pinnule, spanning the midvein and one margin containing sporangia. The fluorescence 2D

255 XANES imaging consisted of forming ‘stacks’ of μ XRF images by scanning the sample area
256 multiple times at successive incident energies. As such, the sample was raster-scanned over a 2.380
257 \times 1.295 mm window with a 5 μ m step size, resulting in a μ -XANES image stack of 477 \times 260
258 pixels. The sample was scanned over the As K-edge ($11\ 877$ eV) at 112 energies from $11\ 800$ to 12
259 100 eV using 2 eV steps across the pre-edge region ($11\ 800$ to $11\ 855$ eV), 0.5 eV steps across the
260 XANES region ($11\ 855$ to $11\ 900$ eV) and 20 eV across the post-edge region ($11\ 900$ to $12\ 100$ eV).
261 The μ -XANES spectra were measured using the Maia detector array with a ~ 1.7 ms per pixel dwell
262 time.

263

264 Arsenic ‘hotspots’ were identified from the confocal μ XRF images as regions of interest for
265 volumetric XANES point measurements. Of particular interest is the reduction of arsenate to arsenite
266 as As species cross from the vascular system to the leaf tissues, so regions were selected in the
267 (tissues listed in decreasing proximity to main vascular system) midvein, endodermis, mesophyll and
268 epidermis as well as regions in the secondary veins (vein bundles and surrounding protective
269 sheaths) and sporangia (reproductive parts of the fern). In order to obtain spatial coordination, first
270 coarse confocal μ XRF maps were made of the sample. Volumetric XANES point measurements
271 were acquired using the confocal optic attached to a Vortex SDD detector (as described above) and
272 measured across the As K-edge ($11\ 877$ eV) at 100 energies spanning the energy range $11\ 802$ to
273 $12\ 017$ eV in 0.25 eV steps with 0.5 s dwell.

274

275 Energy calibration at the XFM beamline was achieved using a sample of solid sodium arsenite
276 diluted in boron nitride. The “white line” peak energy of this sample was assumed to be 11874.4 eV.

277

278 The 2D μ XRF and single-slice μ XRF tomography measurements carried out in the microprobe of
279 P06 at DESY were performed with a beam size of 532 \times 444 nm at an incident energy of 14 keV.
280 Considering a minimum step size of 0.5 μ m and comparing it to the size of the beam, the resolution
281 of the resulting images can be treated as being equal to the step size. Samples consisted of a free-
282 standing rachis and two pinnule margins, one mounted between Ultralene films for 2D measurements
283 and the other mounted inside a Kapton capillary for tomography. All scans were conducted in
284 continuous-scanning mode to minimize dead-time between the exposures with dwell times between 1
285 ms and 10 ms. In the case of single-slice tomography, the rotation stage was the slow scanning axis
286 and the longer scans of the rachis were divided into eight interlaced sub-scans to account for possible
287 vertical drift of the sample. All the samples were either freeze-dried (rachis) or dehydrated (pinnule
288 margin) and so a cryo-stream was not employed.

289 **2.6 Sample preparation and measurement conditions**

290 All frozen-hydrated samples were scanned in using a cryo-stream, whereas the freeze-dried samples
291 were scanned at room temperature (20°C). Individual freeze-dried pinnules were glued to carbon
292 sticks with cyanoacrylate (Fig 1b,c), but larger samples (*i.e.* the intact ‘fresh/live’ frond) were
293 sandwiched between two sheets of Kapton thin film (4 μm) stretched over a Perspex frame (Fig 1d)
294 magnetically attached to the *x-y* motion stage at atmospheric temperature (~20°C). The samples were
295 scanned ‘on-the-fly’ with a 1–5 ms per pixel dwell at an incident energy of 15.8 keV. The frozen-
296 hydrated samples were transferred under the N₂ cryo-stream (-100°C) and were maintained at dry ice
297 temperature during transfer – as such they were kept under cryogenic conditions from collection
298 through to the completion of measurement.

299

300 **2.7 Data analysis**

301 The Maia X-ray fluorescence data were analysed using GeoPIXE^{54,55}, and images were generated
302 using the Dynamic Analysis method^{56,57}. Unfortunately, due to a technical error associated with the
303 data writing to the cluster storage the raw data of a number of 2D μXRF elemental maps were
304 irretrievably lost. However, real-time (RT) processing data from GeoPIXE were locally retained, and
305 the corresponding pseudo-elemental maps are included in the Supplementary Information.

306

307 Self-absorption, which can lead to inaccuracy in the determination of elemental concentration by
308 XRM, especially in ‘thicker’ samples, depends on the composition of the material, on the thickness
309 of the sample, on the localisation of the element to be detected and on the element itself (energy of
310 its X-ray fluorescence lines), on the distance between sample and the detector, on the energy of the
311 incident beam. Assuming that fern tissue has a similar composition and density to that of cellulose
312 (C₆H₁₀O₅) with an average thickness of 300 μm (a pinnule blade is somewhat thinner at ~80 μm
313 whereas a rachis is thicker at ~500 μm) and a density of 1.0 g cm⁻³ then it is assumed that the As
314 fluorescence (K_{alpha} line at 10.5 KeV) maximum absorption on escape is ~10%.

315

316 Confocal XRF imaging data were analysed with MAPS. Because the (element-dependant)
317 transmission efficiency of the polycapillary optic is not known, and because of the different
318 geometric orientations of the sample (resulting in varying X-ray flux on the sample), the confocal
319 elemental maps were not quantified with respect to concentrations of particular elements. The
320 concentrations are hence plotted on a relative scale.

321

322 Analysis of the XFM- μ CT data was achieved by alignment steps using consistency and cross-
323 correlation methods to correct for horizontal drift in the sinograms followed by a tomographic
324 reconstruction step. The high angular sampling of the rachis allowed reconstruction using a filtered
325 back-projection algorithm. However, the pinnule sinograms were recorded with lower angular
326 sampling and so were reconstructed with a maximum-likelihood expectation-maximization algorithm
327 based on the functions of the *scikit-image* image processing library.

328

329 Fluorescence-XANES mapping gave a 3D image stack of spatial dimensions (x, y) and an X-ray
330 incident energy-resolved dimension E . Initially, the XANES images were aligned using a well-
331 featured spectator element. Alternatively, one could consider each pixel (x, y) of the 477×260 -pixel
332 image stack to be associated with a unique XANES spectrum. The energy variation in the
333 fluorescence spectra were identified using principal component analysis (PCA) allowing for up to six
334 principal components, with the calculations performed using the Multivariate ANalysis Tool for
335 Spectromicroscopy (MANTiS, Lerotic). Pixels possessing similar spectra were grouped together by
336 k -means clustering, identifying three distinct clusters associated with the leaf, vein and image
337 background (Figure 10). The cluster associated with the background of the image has been
338 subtracted from composite image in Figure 10.

339

340 **3. RESULTS.**

341

342 **3.1 Bulk chemistry and anatomical features**

343 Although *P. vittata* can reach up to $22\,600\ \mu\text{g g}^{-1}$ As dry weight in its fronds⁴, the cultured plants
344 display $1354\ \mu\text{g g}^{-1}$ and field collected plants from China have $8580\ \mu\text{g g}^{-1}$ As on a dry weight basis
345 (Table 2). The concentration of Ca is relatively high in the pinnae with up to $10\,300\ \mu\text{g g}^{-1}$, whereas
346 the K concentration is extremely high in both the pinnae and rachis ranging from $12\,300$ to $33\,000$
347 $\mu\text{g g}^{-1}$. The concentration of P is exceptionally high, especially in the samples from China with up to
348 $62\,700\ \mu\text{g g}^{-1}$ in the pinnae and up to $67\,000\ \mu\text{g g}^{-1}$ in the rachis. Concentrations of Cu, Zn and Fe are
349 unremarkable. Toluidine blue stained *P. vittata* sections of the rachis (Fig. 2) show the typical
350 anatomy of a pteridophyte with the C-shaped elliptical vascular bundles surrounded by three-cell
351 thick pericycle and endodermis cells. The mesophyll is not differentiated into palisade and spongy
352 parenchyma, and mesophyll is absent from the mid-rib. Scanning Electron Microscopy (SEM)
353 images show details of the sporangium with sporophytes (Fig. 3). Each sorus contains clusters of
354 sporangia protected by the upper indusial flap ('false indusium') that is formed by the margins of the

355 pinnule. The abundant presence of fertile cells is evident with the sporangium showing individual
356 sori enclosed by large annulus cells.

357

358 **3.2 Planar elemental imaging, confocal ‘virtual’ and computed tomography slices**

359 The 2D projection μ XRF elemental maps of the live frond (Fig. 4) show substantial enrichment of
360 As in the vascular bundles, particularly in the rachis, but also in the veins of the pinnule. There is a
361 depletion of As in the interveinal areas of the pinnule. The localisation of K is similar except that its
362 concentration in the rachis is higher than the mean As concentration in fronds. In contrast, Ca is
363 depleted in the rachis, but enriched in the veins of the pinnule particularly towards the terminal ends.
364 Calcium is also enriched in damaged (chlorotic) parts of the fronds, mainly along the margins. These
365 differences are more pronounced in the high-resolution scans of the pinnule apex (Fig. 5), with Ca
366 depleted in the veins but enriched along the pinnule margins. The distribution of As and K are again
367 similar although the distribution of K extends into the lamina. In the freeze-dried pinnule portion
368 towards the terminus (Suppl. Fig. S1 A, B), the distribution of As mirrors that of the frozen-hydrated
369 samples with substantial enrichment in the vascular bundles, especially in the central vein. In fertile
370 pinnules (Suppl. Fig. 1, C, D) strong accumulation of As in the sorus and sporangia is visible.
371 Further detail can be gleaned from scans of the sori (Suppl. Fig. 2). Apart from As enriched in the
372 indusium, the strongest accumulation occurs in the annulus of each sporangium. Some of the
373 individual spores are also rich in As (see top-right panel, Fig. 9), as are hairs in the sorus (for
374 example bottom right panel Fig. 9). Enrichment in the hairs that guard the sporangium at the margin
375 of the fronds has been noted previously²⁵.

376

377 Higher resolution 2D μ XRF images (up to 0.5 μ m) were collected of the (freeze-dried) pinna margin
378 containing the indusium covering the sporangia, which reveals that As is enriched predominantly in
379 the vascular bundles connecting to the sporangia, but little in the sori themselves (Suppl. Figs. 6, 7,
380 and 8). K is enriched along the indusium edge, and Zn highly localised in the mature sori.
381 Fluorescence computed μ -tomography slices and projections of an intact pinna (Fig. 8 and 9, 0.5 μ m
382 pixels) similarly reveal As enrichment in the vascular structures, especially in nodes, but also in
383 some sori.

384

385 Elemental maps of As, Br, Ca and Rb obtained from confocal ‘virtual’ cross-sections of a pinnule are
386 shown in Suppl. Fig. 9. The self-absorption effect as a function of element z is clearly visible from
387 the Ca elemental map with a ‘shadow’ evident behind the thicker midrib. For that reason, we have
388 plotted maps of (high Z) Rb and Br to serve as proxies for K and Cl respectively. The elemental

389 distribution of Rb is similar to As, which was expected on the basis of the earlier observed
390 similarities between As and K. Arsenic is localised in the adaxial (upper) epidermis extending into
391 the palisade mesophyll. Arsenic is also strongly enriched in the phloem of the (sub)lateral veins.
392 Confocal cross-sections of the central part of the pinnule with the midrib reveal that As is strongly
393 accumulated in the endodermis and pericycle surrounding the phloem (Fig. 6). Arsenic is also
394 strongly enriched in abaxial (lower) epidermal cells of the midrib (but not extending to the lamina).
395 Detailed confocal scans of the pinnule margins show accumulation of As in the indusium as well as
396 in the sporangia, particularly the annulus (Suppl. Fig 10).

397

398 The elemental distribution of As in freeze-dried physical cross-sections scanned in 2D (Suppl. Fig.
399 3–4) also shows strong enrichment in the endodermis and pericycle surrounding the vascular
400 bundles, as well as in the hypodermis extending into the cortex, ostensibly in the apoplastic space
401 between the cells. Again, As is accumulated in the indusium and in the annulus of the sporangia. A
402 scan of a physically sectioned freeze-dried rachis (Suppl. Fig. 5) shows the accumulation of As in the
403 endodermis and pericycle surrounding the phloem. Fluorescence computed μ -tomography with 0.5
404 μm pixel size was undertaken on a freeze-dried rachis (Fig. 7) and reveals a very similar As
405 enrichment pattern in the endodermis and pericycle surrounding the vascular bundles.

406

407 **3.3 XANES imaging and volumetric XANES spot analysis**

408 2D XANES imaging was performed on a frozen-hydrated pinnule. In addition, volumetric XANES
409 measurements were acquired from spatial regions of interest in pinnae in both freeze-dried samples
410 recorded at room temperature (Suppl. Figs. 11 and 12) and frozen-hydrated state under a cryostream
411 using a confocal optic.

412

413 The cluster spectra associated with the pinnule and vascular bundle areas respectively were
414 compared to reference spectra of relevant As standards (figure 10C). On the basis of the energy
415 position of the absorption maxima, and comparison to the spectrum of solid sodium arsenite recorded
416 during the same beamtime run, cluster 1 and 2 spectra were assumed to correspond to As(III) (as
417 arsenite) and As(V) (as arsenate), respectively. Both spectra are slightly broadened in comparison
418 with reference spectra reproduced from previous study²⁵ that were recorded with higher energy
419 resolution (0.2 instead of 0.5 eV). However, the spectrum extracted from cluster 2 in Fig 10,
420 primarily representing the main vascular bundle zone, displays an even broader absorption edge,
421 displaying a shoulder at lower energy consistent with the peak energy of the arsenite model

422 spectrum. This broadening is likely due to the presence of a mixture of As(III) and (V) species in the
423 vascular bundles, where the relative abundance of each species is consistent across the cluster.

424

425 Volumetric XANES point measurements from a selection of different anatomical features returned
426 spectra that were distinct from the model compound spectra. Absorption peak energies were aligned
427 more closely to those of the As(III) standards, even in tissues where As(V) would be expected from
428 previous work and from the 2D XANES imaging in this work (Figure 10). For instance, it is
429 expected that the vascular bundles (regions G and H, Suppl Fig. 11) would exhibit As(V) prior to
430 crossing the endodermis, however these bundles display reduced As(III) as stated from the peak
431 energy. The peak height to background edge jump ratio in several of the volumetric XANES spectra
432 is drastically attenuated relative to the model spectra. The results of the volumetric XANES analysis
433 suggest that this approach delivers too high of a radiation dose to the sample to be reliable in
434 determining the speciation of As in the specimen without drastic photoreduction, even in samples
435 cooled under a liquid N₂ cryostream. In fact, point XANES spectra from freeze-dried tissues (Suppl
436 Fig 12), which should be less susceptible to photoreduction due to the absence of water, show higher
437 peak energies in some cases compared to those spectra from frozen tissue, strongly implicating
438 photodamage in the unusual appearance of these spectra.

439

440 The XANES spectra collected using either 2D XANES imaging or confocal point XANES are
441 compared below to model As compound spectra previously reported²⁵. We note that the spectral
442 resolution of the beamline used in this work is significantly poorer than that from the previous work;
443 as such, any comparison should be interpreted with caution as the spectra from this study will be
444 broadened significantly compared to the model compound spectra.

445

446 **4. DISCUSSION**

447 The use of confocal optics has made it possible to examine As in the depth profile of the tissues in
448 physically intact samples with high aspect ratio, without the need for destructive sample preparation,
449 and this approach has provided new information on the mechanisms underlying As
450 hyperaccumulation in *P. vittata*. Confocal cross-sections of the central part of the pinnule with the
451 midrib have revealed that As is strongly accumulated in the endodermis and pericycle surrounding
452 the phloem. XFM μ -CT revealed a very similar As enrichment pattern in the endodermis and
453 pericycle surrounding the vascular bundles. As such, the various technical approaches lead to
454 conclusions that are entirely consistent with each other.

455

456 Confocal optics also offer the ability to perform volumetric XANES to obtain spatially resolved
457 information on the chemical speciation within intact tissues. However, it eventuated that volumetric
458 XANES causes substantial photodamage due to the very high radiation dose of this approach (60s
459 total exposure per point), even if the sample is cryogenically cooled. Therefore, observations indicate
460 that significant interpretation regarding As chemical form should not be drawn from the confocal
461 volumetric XANES measurements, and reiterate the utility of 2D XANES imaging to provide
462 chemical information with lower X-ray dose (0.0017s total exposure per pixel, or ~300 less than then
463 confocal XANES measurements), albeit without the capacity to provide information in the third
464 dimension in this case. The results of the 2D XANES imaging are congruent with previous
465 knowledge of As speciation in *P. vittata*²⁵, which in part validates the novel confocal imaging in this
466 work as it demonstrates that the sample preparation has not modified the distribution of the primary
467 arsenic species in the tissues. Published 2D XANES imaging studies showed that different chemical
468 forms of As (As(III) and As(V)) occur across the plant organs²⁵. Depth information of As chemical
469 speciation in different cell types within tissues of *P. vittata* was not available and the knowledge of
470 the distribution across different cells types within the fronds and rachis was limited²⁸. In this work
471 we have demonstrated that observed differences in As speciation across tissues are related to spatial
472 variation of As concentration in different cell types.

473

474 After the Zn-Ni-Cd hyperaccumulator *Noccaea caerulescens*, *P. vittata* is the most well-studied
475 hyperaccumulator. As a consequence, much is now known about the uptake and metabolic regulation
476 of As in this species^{19,21,22,26,25,28,31,30}. Nevertheless, many open questions remain, specifically
477 surrounding the adaptive advantages for As hyperaccumulation in this species, and about the
478 physiological functions of As(V) to As(III) conversion for storage and translocation in the fronds.

479

480 **Author contributions**

481 M.L and X-M.W collected the *P. vittata* samples in the field in China. A.vdE cultivated live *P.*
482 *vittata* in Australia. X-M.W prepared freeze-dried samples for the synchrotron analysis. A.vdE,
483 M.dJ, E.M-P, G.E. and H.H.H conducted the synchrotron XFM experiments. M.dJ, R.MP and H.H.H
484 analysed the XFM and XAS data. A.vdE performed the SEM-EDS and light microscopy
485 experiments. A.vdE, K.M.S and D.B performed the synchrotron μ XRF tomography experiments.
486 K.M.S analysed the μ XRF tomography spectra. D.B reconstructed the μ XRF tomograms. All authors
487 contributed to writing the manuscript.

488

489

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504

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725

726 **FIGURE CAPTIONS**

727

728 **Figure 1.** Experimental setup at the XFM beamline of the Australian Synchrotron: **[A]** Schematic
729 diagram of confocal probe, SDD – silicon drift detector (image by Gary Ruben) **[B]** frozen-hydrated
730 sample under the cryo-stream in front of the Maia detector; **[C]** Frozen-hydrated samples probed
731 with the confocal optic; **[D]** Maia planar imaging at room temperature of a large live frond still
732 attached to the plant (with rhizome in pouch with moist cotton). Typical dimensions of the probe
733 beam are $\sim 1 \mu\text{m}$, those of the confocal field of view are $\sim 10 \mu\text{m}$, and the specimen thickness is in the
734 $>100 \mu\text{m}$ domain.

735

736 **Figure 2.** Toluidine blue stained *Pteris vittata* sections: **[clockwise from top left]** section of the
737 rachis; section of the central part of the frond; unstained and stained sections of the sporophytes
738 attached to the frond. Abbreviations: *LE* lower epidermis, *UE* upper epidermis, *C* cortex, *P* pamenta,
739 *VB* vascular bundle, *Ct* cuticle, *H* hypodermis, *M* mesophyll, *X* xylem, *E* endodermis, *Pe* pericycle,
740 *Ph* phloem, *R* receptacle, *I* false indusium, *Ha* hair, *Ys* young sporangium, *Ms* mature sporangium, *A*
741 annulus, *S* stomium.

742

743 **Figure 3.** Scanning Electron Microscopy (SEM) images of *Pteris vittata* tissues: **[A]** sporangium
744 enclosures within the margin of the frond (indusium); **[B]** detail of sporophytes showing **[C]** vascular
745 bundles of the rachis; **[D]** detail of central xylem bundles.

746

747 **Figure 4.** Planar μXRF maps of Ca, K and As of a live *Pteris vittata* frond examined at room
748 temperature. Relative concentrations are depicted by shading with brighter colours equating to higher
749 concentrations ('heatmap').

750

751 **Figure 5.** Planar μXRF maps of Ca, K, As and Compton Scatter of the terminal ends of a live *Pteris*
752 *vittata* frond examined at room temperature. Relative concentrations are depicted by shading with
753 brighter colours equating to higher concentrations ('heatmap').

754

755 **Figure 6.** Confocal μXRF virtual section elemental maps of As in *Pteris vittata* fronds (central
756 part/rachis). Panels: **[A]** freeze-dried f examined at room temperature; **[B]** frozen-hydrated examined
757 under the cryostream; **[C]** freeze-dried f examined at room temperature; **[D]** frozen-hydrated
758 examined under the cryostream. Relative concentrations are depicted by shading with brighter
759 colours equating to higher concentrations ('heatmap').

760 **Figure 7** Single-slice μ XRF tomogram of a freeze-dried *Pteris vittata* rachis examined at room
761 temperature showing As and Compton signals. Relative concentrations are depicted by shading with
762 brighter colours equating to higher concentrations ('heatmap').

763

764 **Figure 8.** Single-slice μ XRF tomograms of a freeze-dried *Pteris vittata* pinnule margin inside a
765 Kapton capillary examined at room temperature showing As and Compton signals. Relative
766 concentrations are depicted by shading with brighter colours equating to higher concentrations
767 ('heatmap').

768

769 **Figure 9.** 2D μ XRF maps of a freeze-dried *Pteris vittata* pinnule margin inside a Kapton capillary
770 examined at room temperature showing As and Compton signals from different angles. Relative
771 concentrations are depicted by shading with brighter colours equating to higher concentrations
772 ('heatmap').

773

774 **Figure 10.** *Left:* As elemental map of a portion of *Pteris vittata* pinnule including midvein and leaf
775 margin, taken at the top energy of the 2D XANES imaging scan (12.1 keV). *Middle:* composite of
776 cluster maps generated by k -means clustering analysis with $k = 3$. Cluster 1 is shown in blue and
777 cluster 2 is shown in red, the third cluster associated with the image background has been set to
778 white. *Right:* the spectra of cluster 1 and cluster 2 reconstructed from principal components
779 compared to reference As standards. The sample is frozen-hydrated examined under the cryostream.
780 Relative concentrations are depicted by shading with brighter colours equating to higher
781 concentrations ('heatmap').

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787 **TABLE CAPTIONS**

788

789 **Table 1.** Comparison of synchrotron X-ray methodological approaches that are available to an
790 experimenter at XFM beamlines to interrogate As distribution and chemical speciation in *Pteris*
791 *vittata* tissues. The exact values will change with the beamline.

792

793 **Table 2.** Bulk elemental concentrations in fronds of *Pteris vittata* (values as ranges and means in μg
794 g^{-1} dry weight) with ICP-AES.

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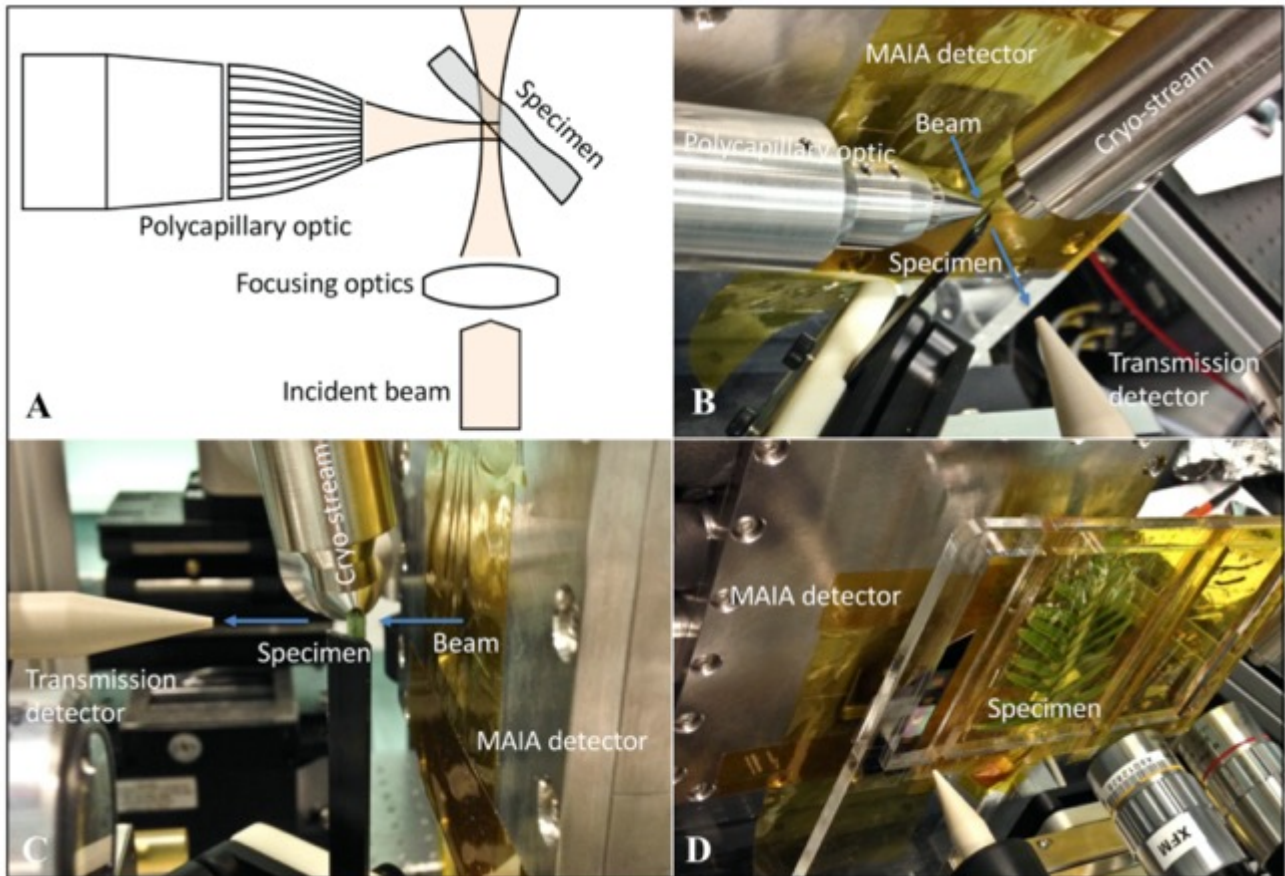
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797 **Supporting Information**

798

799 Planar μ XRF maps of As distribution in dehydrated *Pteris vittata* pinnule (Figure S1). Planar μ XRF
800 maps of As distribution in dehydrated *Pteris vittata* pinnule (Figure S2). Planar μ XRF maps of As
801 and K of a dehydrated cross-sectioned *Pteris vittata* pinnule (central portion) (Figure S3). Planar
802 μ XRF maps of As and K of a dehydrated cross-sectioned *Pteris vittata* pinnule (Figure S4). Planar
803 μ XRF maps of As and K of a dehydrated cross-sectioned *Pteris vittata* rachis (Figure S5). Planar
804 μ XRF maps of the K, As, Zn and Compton signals of a dehydrated *Pteris vittata* pinnule margin
805 (Figure S6). Planar μ XRF maps of the K, As, Zn and Compton signals of a dehydrated *Pteris vittata*
806 pinnule margin (Figure S7). Planar μ XRF maps of the K, As, Zn and Compton signals of a
807 dehydrated *Pteris vittata* pinnule margin (Figure S8). Confocal μ XRF maps of As, Br, Ca and Rb in
808 a freeze-dried *Pteris vittata* pinnule showing the varying degrees of self-absorption depending on
809 element z (Figure S9). Confocal μ XRF maps of As in *Pteris vittata* pinnule (terminal
810 end/sporangium) (Figure S10). As fluorescence map from confocal μ XRF imaging of *P. vittata*
811 sporangia recorded using the Vortex SDD from an incident beam energy of 15.8 keV, showing the
812 locations of the volumetric XANES measurements taken at the sporangia, As fluorescence map from
813 confocal μ XRF imaging of *P. vittata* midvein, volumetric XANES spectra taken from the ROIs
814 identified (Figure S11). Supplementary Figure 12. As fluorescence map from confocal μ XRF
815 imaging of *P. vittata* sporangia, volumetric XANES spectra taken from the ROIs identified (Figure
816 S12). Bright-field microscopy images of transversely cut sections of *Pteris vittata* samples (Figure
817 S13).

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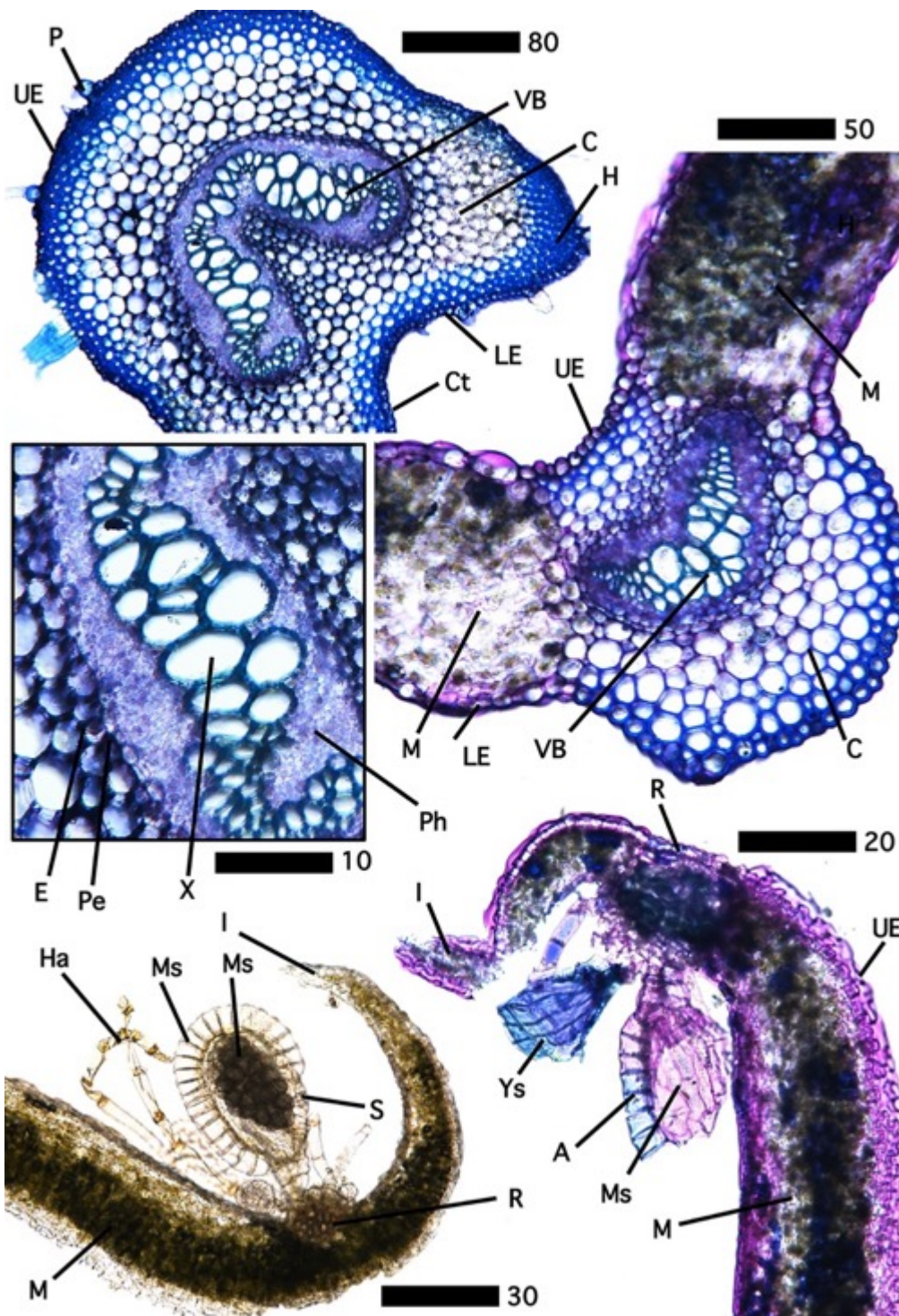
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821 **Figure 1.** Experimental setup at the XFM beamline of the Australian Synchrotron: [A] Schematic
 822 diagram of confocal probe, SDD – silicon drift detector (prepared by Gary Ruben) [B] frozen-
 823 hydrated sample under the cryo-stream in front of the Maia detector; [C] Frozen-hydrated samples
 824 probed with the confocal optic; [D] Maia planar imaging at room temperature of a large live frond
 825 still attached to the plant (with rhizome in pouch with moist cotton). Typical dimensions of the probe
 826 beam are $\sim 1 \mu\text{m}$, those of the confocal field of view are $\sim 10 \mu\text{m}$, and the specimen thickness is in the
 827 $>100 \mu\text{m}$ domain.

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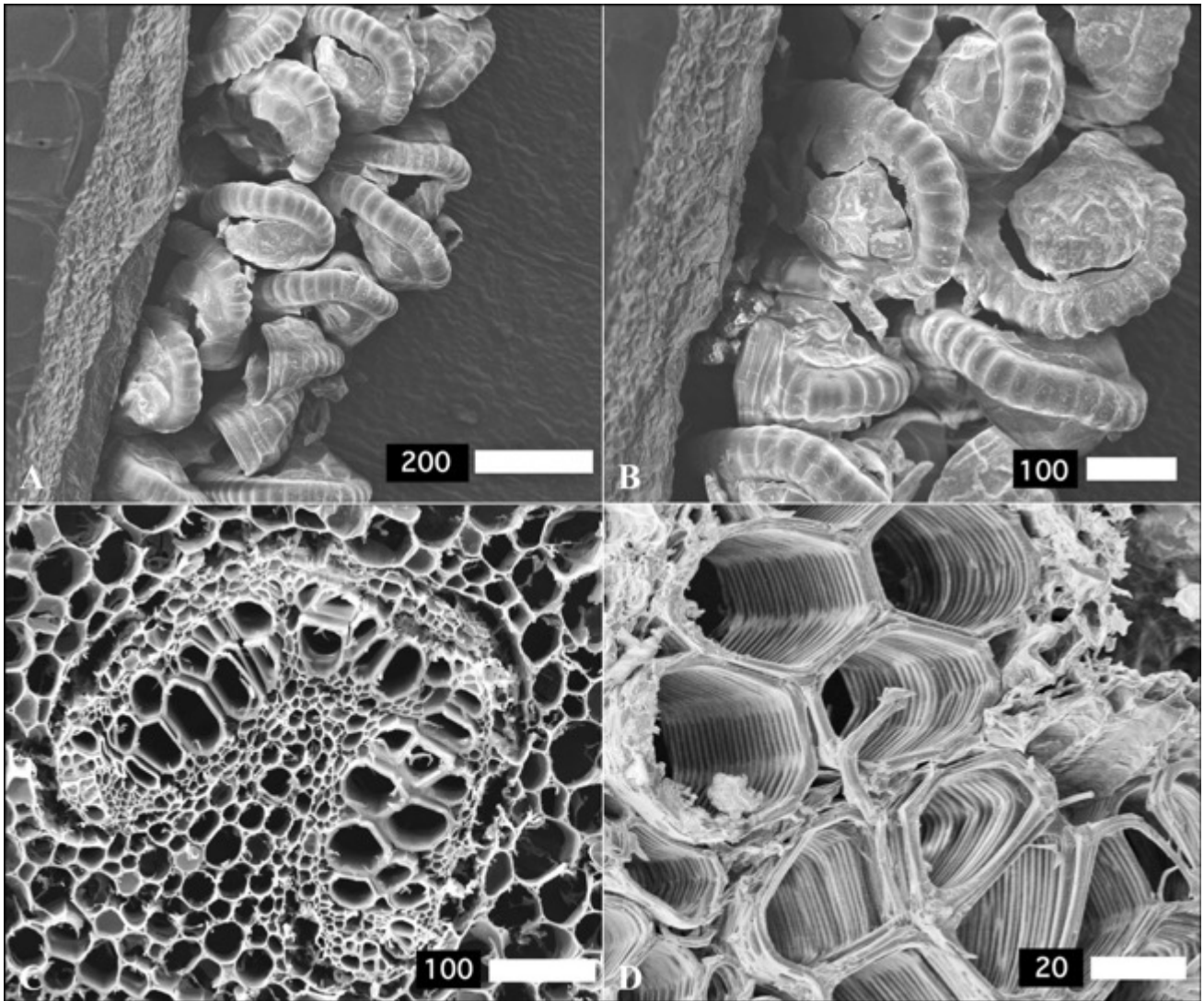
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832 **Figure 2.** Toluidine blue stained *Pteris vittata* sections: [clockwise from top left] section of the
 833 rachis; section of the central part of the frond; unstained and stained sections of the sporophytes
 834 attached to the frond. Abbreviations: *LE* lower epidermis, *UE* upper epidermis, *C* cortex, *P* pamanta,
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 836 *Ph* phloem, *R* receptacle, *I* false indusium, *Ha* hair, *Ys* young sporangium, *Ms* mature sporangium, *A*
 837 annulus, *S* stomium. Scale bars denote μm .



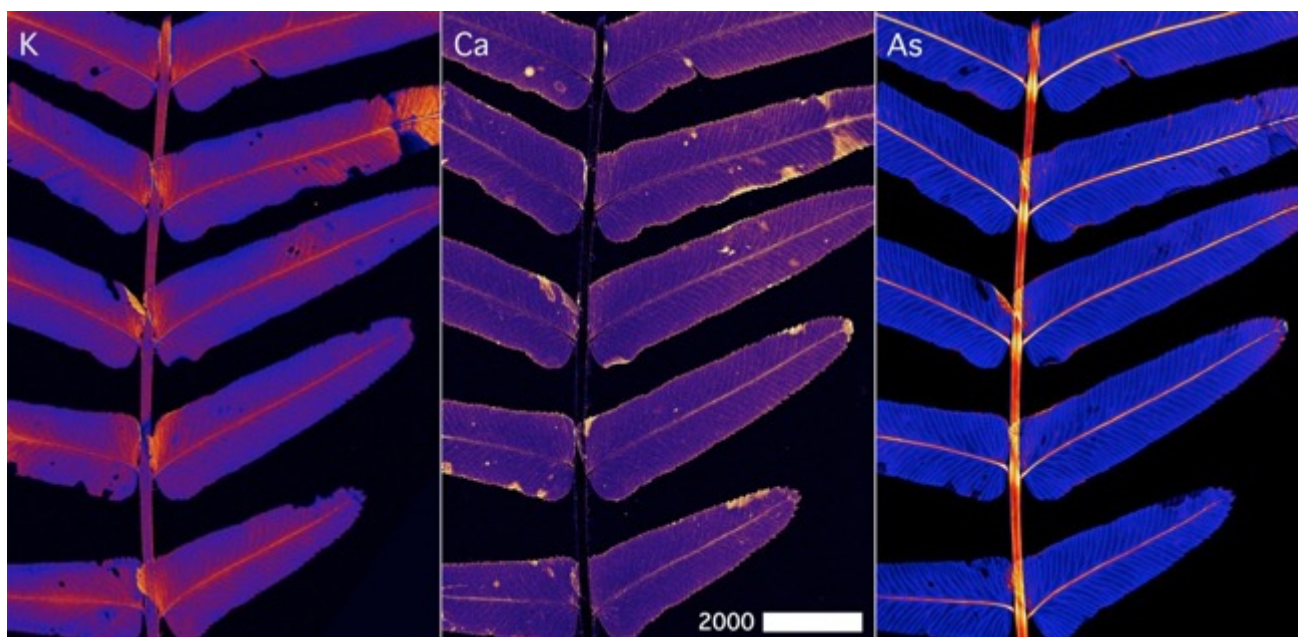
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842 bundles of the rachis; [D] detail of central xylem bundles. Scale bars denote μm.

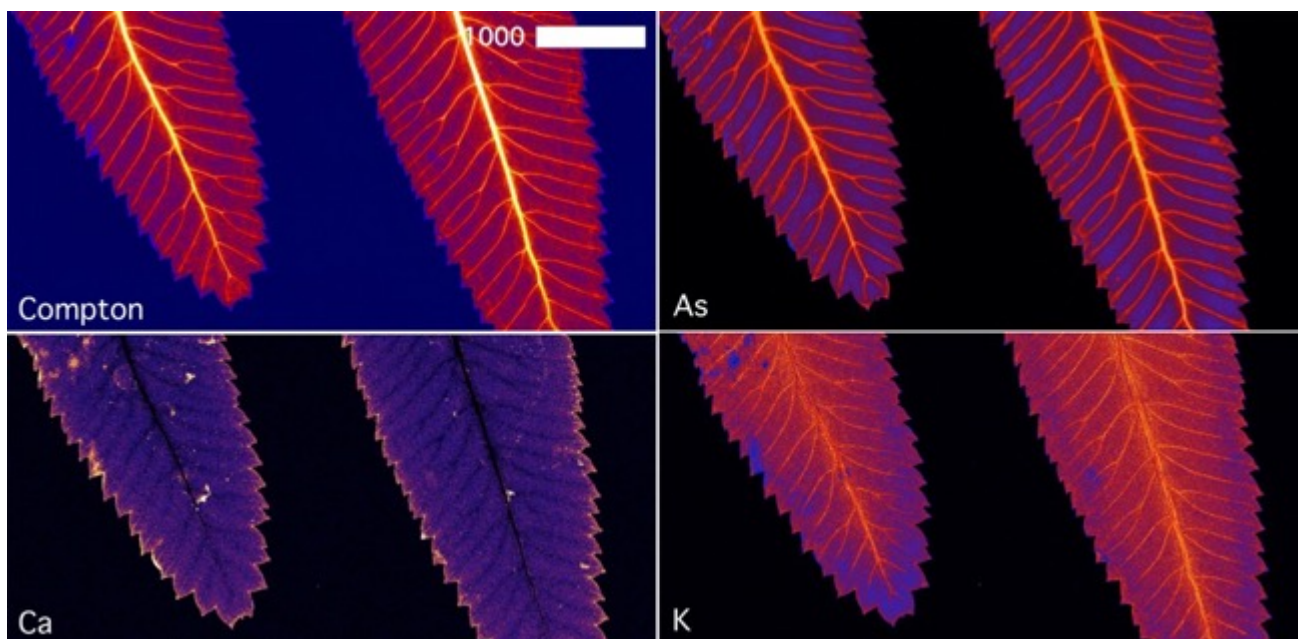
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Figure 4. Planar μ XRF maps of Ca, K and As of a live *Pteris vittata* of a partial frond with pinnae examined at room temperature. Relative concentrations are depicted by shading with brighter colours equating to higher concentrations ('heatmap'). Scale bars denote μm .



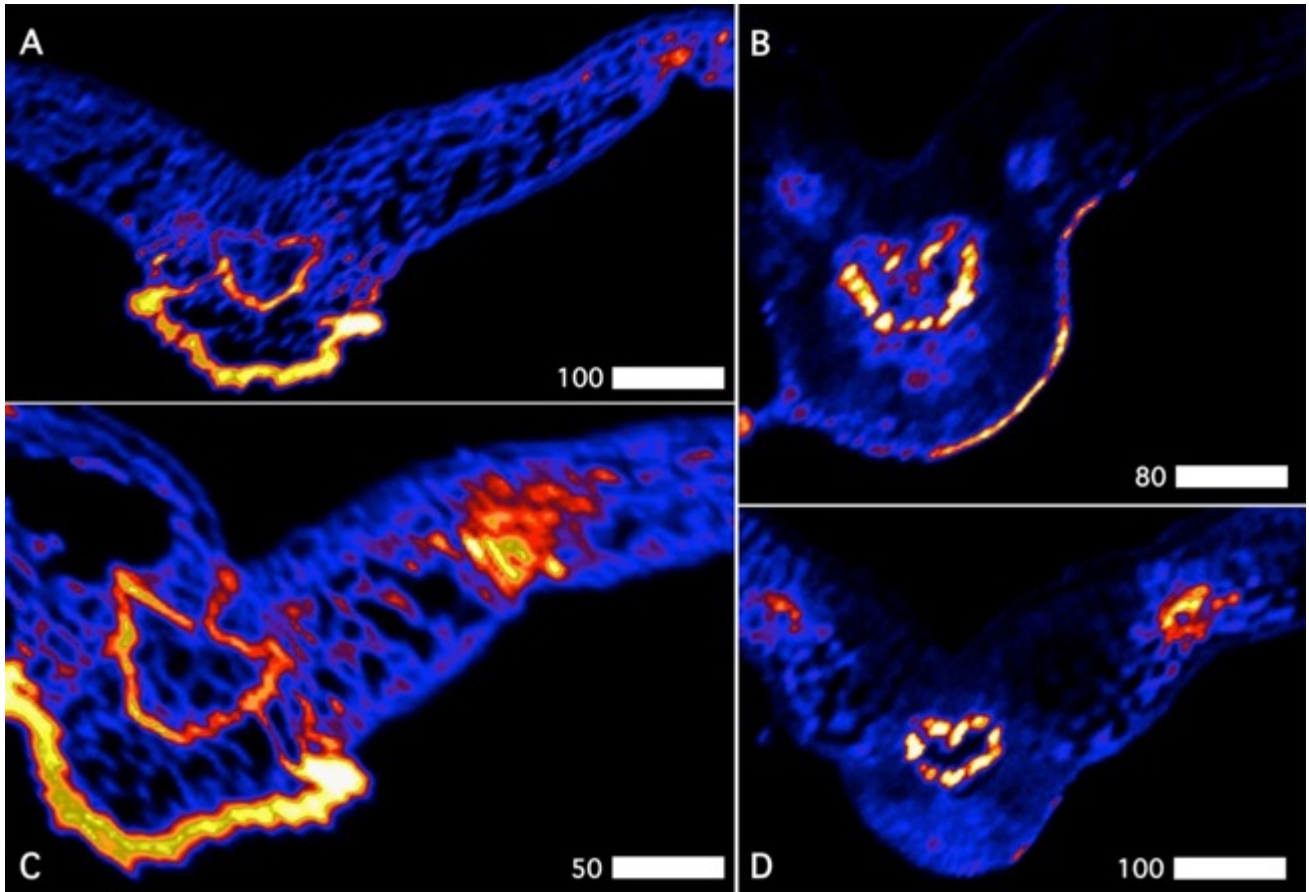
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854 **Figure 5.** Planar μ XRF maps of Ca, K, As and Compton Scatter of the terminal ends of a live *Pteris*
855 *vittata* pinnules examined at room temperature. Relative concentrations are depicted by shading with
856 brighter colours equating to higher concentrations ('heatmap'). Scale bars denote μ m.

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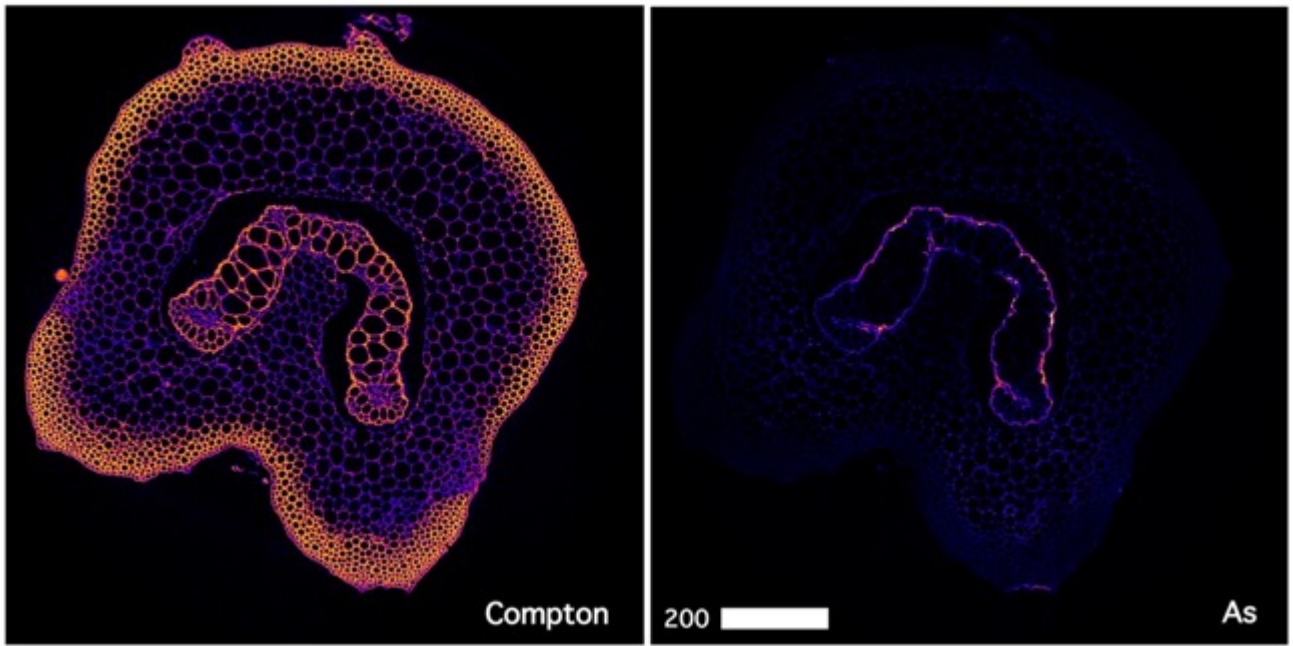
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861 **Figure 6.** Confocal μ XRF virtual section elemental maps of As in *Pteris vittata* pinnules (central
 862 part/rachis). Panels: **[A]** freeze-dried f examined at room temperature; **[B]** frozen-hydrated examined
 863 under the cryostream; **[C]** freeze-dried f examined at room temperature; **[D]** frozen-hydrated
 864 examined under the cryostream. Relative concentrations are depicted by shading with brighter
 865 colours equating to higher concentrations ('heatmap'). Scale bars denote μm .

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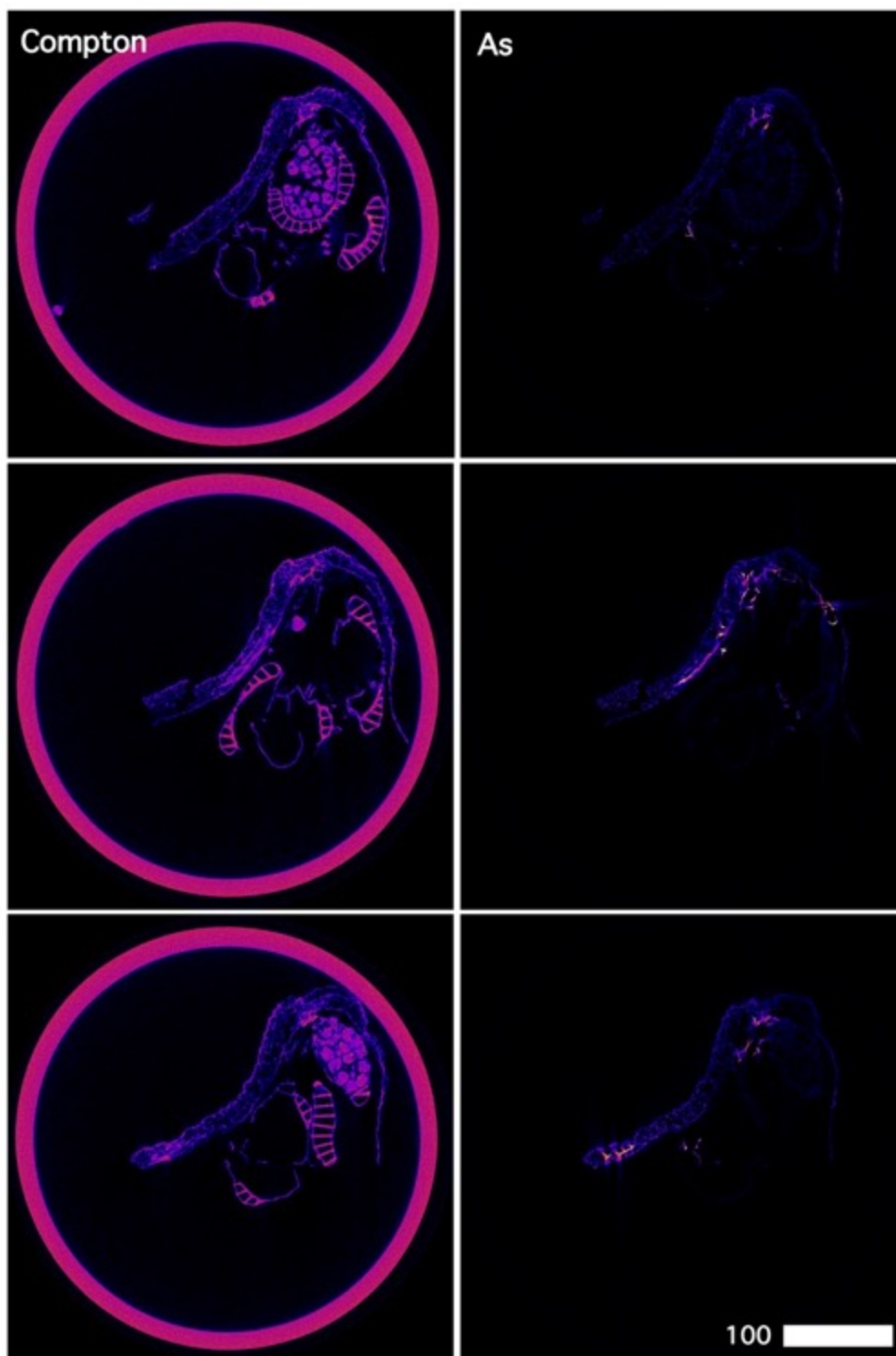
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870 **Figure 7** Single-slice μ XRF tomogram of a freeze-dried *Pteris vittata* rachis examined at room
871 temperature showing As and Compton signals. Relative concentrations are depicted by shading with
872 brighter colours equating to higher concentrations ('heatmap'). Scale bars denote μm .

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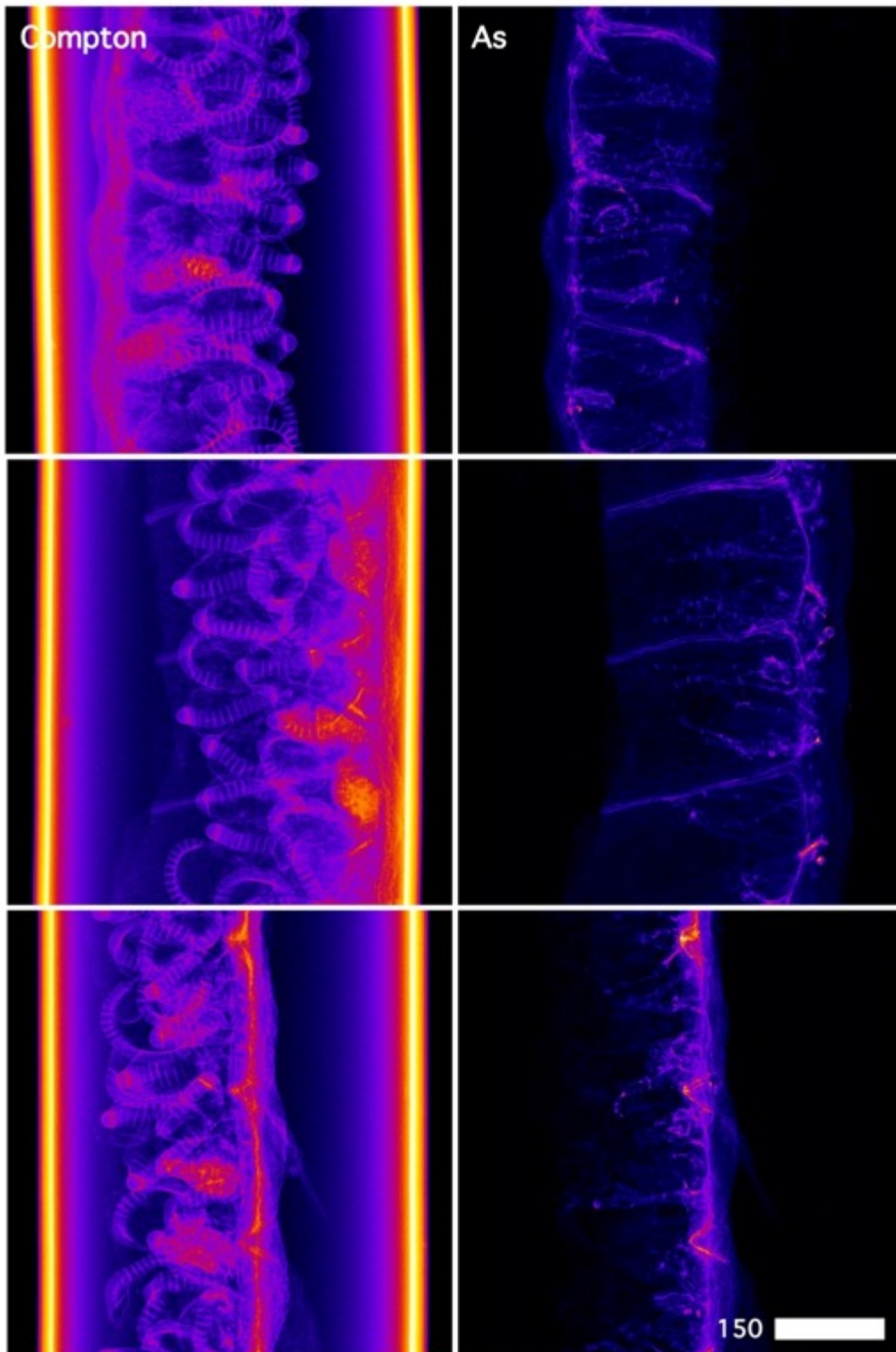


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877 **Figure 8.** Single-slice μ XRF tomograms of a freeze-dried *Pteris vittata* pinnule margin inside a
 878 Kapton capillary examined at room temperature showing As and Compton signals. The same sample
 879 at different depths is shown. Relative concentrations are depicted by shading with brighter colours
 880 equating to higher concentrations ('heatmap'). Scale bars denote μm .

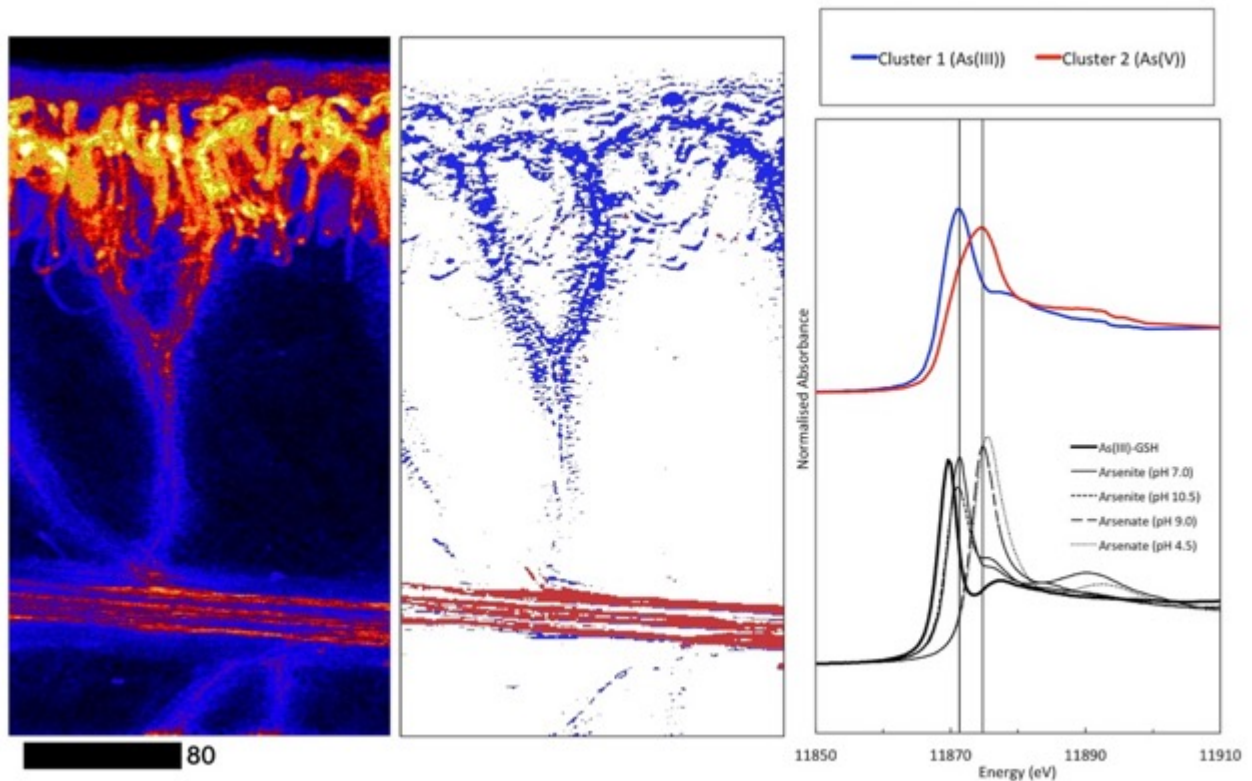
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884 **Figure 9.** 2D μ XRF maps of a freeze-dried *Pteris vittata* pinnule margin inside a Kapton capillary
 885 examined at room temperature showing As and Compton signals from different angles. Relative
 886 concentrations are depicted by shading with brighter colours equating to higher concentrations
 887 ('heatmap'). Scale bars denote μ m.



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890 **Figure 10.** *Left:* As elemental map of a portion of *Pteris vittata* pinnule including midvein and leaf
 891 margin, taken at the top energy of the 2D XANES imaging scan (12.1 keV). *Middle:* composite of
 892 cluster maps generated by *k*-means clustering analysis with *k* = 3. Cluster 1 is shown in blue and
 893 cluster 2 is shown in red, the third cluster associated with the image background has been set to
 894 white. *Right:* the spectra of cluster 1 and cluster 2 reconstructed from principal components
 895 compared to reference As standards. As the energy calibration of the standards was not performed at
 896 the beamline, both cluster spectra have been shifted down in energy by 1 eV to align the peaks more
 897 closely with those of the standards. The sample is frozen-hydrated examined under the cryostream.
 898 Relative concentrations are depicted by shading with brighter colours equating to higher
 899 concentrations ('heatmap'). Scale bars denote μm .

Analysis Type	Specimen preparation	Specimen state	Imaging Modality	X, Y, (Z) resolution [μm]	Positive aspects	Negative aspects
μXRF	Sections	Dry or Frozen-hydrated	Projection imaging	2, 2, (30)	Fast acquisition Section thickness can match cellular length-scales	Disruptive preparation due to freeze-drying and/or sectioning
	Intact tissues	Frozen-hydrated	Projection imaging	2, 2, (none)	Fast acquisition Full specimen immobilisation	Narrow field of view depending on cryogenic implementation No depth information
	Intact tissues	Live hydrated	Projection imaging	0.5, 0.5, (none)	Fast acquisition Potential for sample evolution and degradation during analysis	Potential for radiation damage No depth information
	Intact tissues	Live hydrated / Dry	3D tomography	5, 5, 5	Ability to obtain 3D models of intact specimen	Potential for radiation damage Only for narrow specimen
	Intact tissues	Live hydrated / Dry	2D (single-slice) tomography	0.5, 0.5, 0.5	Acquisition of a single high-resolution virtual slice	Potential for radiation damage Only for narrow specimens
	Intact tissues	Frozen-hydrated	Confocal imaging	2, 2, 10	Direct access to internal volumes within extended specimens	Slower acquisition Increased radiation dose
XANES	--	--	XANES imaging	2, 2, (none)	Overall low radiation dose	No depth information
	--	--	Confocal XANES	2, 2, 10	Directly probes chemical speciation within internal volume	High radiation dose can result in photo-reduction

Table 1. Comparison of synchrotron X-ray methodological approaches that are available to an experimenter at XFM beamlines to interrogate As distribution and chemical speciation in *Pteris vittata* tissues. The exact values will change with the beamline.

Tissue	Origin	Sample preparation	As	Ca	Cu	Fe	K	Mg	Na	P	S	Zn
Pinnae	China	Freeze-dried	6130	4420	21	309	32 100	3650	3960	62 700	4410	93
Pinnae	China	Freeze-dried	8580	4620	29	281	33 000	4290	7190	55 000	4920	35
Pinnae	Cultured	Freeze-dried	777	6700	7.5	390	16 300	2620	1320	17 000	3070	28
Pinnae	Cultured	Freeze-dried	1130	10 300	8.3	203	12 300	3680	927	12 000	3100	40
Rachis	Cultured	Freeze-dried	1080	923	10	142	25 000	715	7702	37 600	1520	48
Rachis	Cultured	Freeze-dried	1350	924	10	171	24 300	682	7900	35 400	1440	34
Rachis	Cultured	Freeze-dried	1140	1620	8.2	145	27 300	1020	6570	34 200	2100	48
Rachis	China	Freeze-dried	4530	5760	16	313	24 900	4110	6740	67 000	3790	93
Whole frond	Cultured	Analysed living	5170	2180	15	152	33 000	2440	4440	27 300	2630	27

Table 2. Bulk elemental concentrations in fronds of *Pteris vittata* (values as ranges and means in $\mu\text{g g}^{-1}$ dry weight) with ICP-AES.