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History of human impact on Moroccan mountain landscapes

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30 ***Abstract***

31 The present study aims to review palaeoecological evidence for environmental changes
32 induced by human activities over the last few millennia in the montane landscapes of Morocco. The
33 study is based on well-dated pollen and geochemical records from the Rif and the Middle Atlas
34 mountains, to show spatial and temporal variation in the onset and intensity of exploitation of
35 forest, soil and mineral resources. Before ca 2000 BP, anthropogenic impact was minimal. At about
36 that time, abrupt changes of the arboreal pollen proportions, with a decline in all tree taxa, indicate
37 a reduction of the forest cover, interpreted as being anthropogenic. In the Rif mountains, increased
38 influx of carbonates (Ca) in the sedimentary records indicates enhanced soil erosion coincident with
39 the reduction in tree cover. In the Middle Atlas, reduced forest cover is linked to geochemical
40 evidence for mining and metallurgy of lead (Pb), copper (Cu), and zinc (Zn). These industrial
41 activities correspond to the expansion of the Roman Empire into Morocco at around 40 AD, and
42 show a decline when the Romans were displaced by the Vandals about five centuries later.

43 **Introduction**

44 Mediterranean ecosystems, including those in Morocco, are well known to have been strongly
45 impacted by human activities over the last few millennia (Ballouche & Marinval, 2003; Lamb et al.,
46 1991; Sadori et al., 2011; Mercuri et al., 2011). However, we still lack clear information about the
47 extent and intensity of early human impact on the natural vegetation of Morocco. Archaeological
48 studies have identified the sites of early human settlement, farming and industry in Morocco
49 (Ballouche & Marinval, 2003; Daugas et al., 2008; López-Sáez & López-Merino, 2008; López-Sáez
50 et al., 2013; Morales et al., 2013; Zapata et al., 2013) but the impact of these human societies on the
51 forest ecosystems and on the overall landscapes are not well known. Palaeoecological records
52 provide insight into both potential natural and anthropogenic vegetation changes, although it is not
53 always possible to distinguish natural disturbances, such as fires, from the small-scale disturbances
54 caused by hunter-gatherers, or by the first pastoral and cultivating farmers. Archaeological sites
55 provide direct evidence of the occurrence of human populations and their activities, but they do not
56 provide information about the impact on the environment and the surrounding landscapes.
57 Palaeoecological records from lake and peatland sediments cannot directly show the presence of a
58 human population, but may provide complementary information at both local and regional scales.
59 Moreover, a regional dataset of fossil pollen records may help reconstruct the changing spatial
60 extent and scale of human impact through time.

61 Lamb et al. (1991) attempted a reconstruction of human impact on the vegetation of the
62 Middle Atlas from four lacustrine pollen records spanning the last few thousand years. They
63 identified forest exploitation in the Middle Atlas as early as 3000 BC using fossil pollen data.
64 However, anthropogenic disturbance seems to have been slight until 2000 BC, when forest
65 clearance and grazing became more intense. At Tigalmamine, human impact first became strongly
66 evident at 2250 ¹⁴C yr BP (ca. 200 BC) with a strong reduction of the forest cover (Lamb & van der
67 Kaars, 1995). At Taguelmam n'Harcha (Lamb et al., 1991) it is even later, around 1720 ¹⁴C yr BP
68 (ca 300 AD), when the presence of cultivated cereals is detected in the pollen record. At Sidi Ali
69 (Lamb et al. 1999), Dayat Iffir and Dayat Afourgagh (Lamb et al., 1991), human impact began
70 around 3000 BP (ca. 1000 BC). According to these palaeoecological studies of the Middle Atlas, it
71 seems that anthropogenic factors became evident only after the first millennium BC (third
72 millennium cal BP).

73 Archaeobotanical data (pollen, seed and charcoal remains) provide direct evidence of human
74 impact, tending to show that activities such as the beginning of farming started much earlier at ca.

75 5600 BC in coastal or near-coastal areas (López-Sáez & López-Merino, 2008; Morales et al., 2013;
76 Zapata et al., 2013). This temporal difference between the palaeoecological and archaeobotanical
77 studies in Morocco may be due either to lack of detail in the Middle Atlas pollen records (which
78 provided "only a broad outline"; Lamb et al., 1991) of human activities, or to a spatial difference
79 between the northern Moroccan coastal sites and those at higher altitude. Indeed, it is likely that this
80 asynchrony between human impact in mountain and coastal areas relates to the cultural capacity to
81 conquer the high mountain areas and the historical development of the Neolithic economy in
82 northern Africa. Other palaeobotanical studies suggest that human impact on Mediterranean
83 ecosystems is often difficult to detect prior to the Bronze Age (around 3000 BC; Mercuri et al.,
84 2011).

85 In any case, the start of human impact in northern Africa poses questions concerning
86 population expansion either from Africa to southwestern Europe or in the opposite direction (Zapata
87 et al., 2013) since there is a clear evidence of land and forest exploitation in the Iberian peninsula
88 since ca. 5500 BC, which became even more evident in the late Holocene (ca. 2100 BC) (López-
89 Sáez et al., 2011a, 2011b; Cortés et al., 2012; Damblon 1991). The role of human activities in the
90 regional fire history should also be taken into account (Damblon 1991, Linstädter & Zielhofer 2010;
91 Gil-Romera et al., 2010).

92 In this paper we extend these earlier studies to other sites in both the Middle Atlas and the Rif
93 mountains, from which we have obtained new, well dated records. These two mountain chains have
94 different geological histories and therefore provide different signatures in the biogeochemical
95 record. We use geochemical elements to identify both the contribution of the geological watersheds
96 through time in the Rif mountains, and metallurgical activity in the Middle Atlas. The fossil pollen
97 data provide a record of ecosystem changes in both of these montane regions, including their forest
98 degradation and dynamics. In the Rif mountains, forest clearance led to strong soil erosion, evident
99 as increased carbonate (Ca) in the sedimentary record. In the Middle Atlas, forest clearance is
100 identified through geochemical elements indicative of prehistoric industrial activity.

101 ***Materials, methods and site descriptions***

102 In the present study we use data from several late Holocene fossil pollen sequences collected
103 in the Rif mountains and in the Middle Atlas (figure 1). The dated material (table 1) shows that
104 these records cover a more extended time span than that of previous investigations. Here we focus
105 on the parts of the records which show the start and the spread of human activities.

106 **A. The Rif mountains records**

107 During the Cenozoic, the collision between the African and European continents generated
108 the Moroccan mountain chains (Gómez et al., 2000; Lamotte et al. 2000; Teixell et al. 2003)
109 including the Rif range that extends along the Mediterranean Sea coast. Geologically, it belongs to
110 the Gibraltar Arc or Alborán Sea geological region (Michard *et al.* 2006). Although the mountains
111 are highly mineralized, only iron ore is mined on a large scale.

112 Today, the annual rainfall in some areas of the Rif reaches 2000 mm. The wettest areas in the
113 west and central parts of the Rif support forests of *Cedrus atlantica*, *Quercus faginea*, *Q. pyrenaica*
114 and *Q. canariensis*, as well as forests of the endangered endemic *Abies pinsapo* var. *marocana*
115 (figure 1). The vegetation composition changes towards the drier eastern part of the Rif, where the
116 forests are dominated by pines (*Pinus halepensis*, *P. pinaster*) with Sandarac (*Tetraclinis*
117 *articulata*). The vegetation is heavily impacted through cutting and clearing which leads to strong
118 soil erosion and the release of components such as hydroxides of iron, alumina, clays and the
119 cations Ca⁺⁺, Mg⁺⁺ and K⁺. The discharge of these elements varies from one landscape to another.
120 As might be expected, isotopic studies using Cesium 137 (¹³⁷C) in northern Morocco show that
121 agricultural lands are more extensively eroded (18-36 t/ha/yr) than the forested areas (<4.5 t/ha/yr;
122 Zouagui et al., 2012).

123

124 **1. Anaasser peat bog**

125 Anaasser peat bog is located near the rural town of Bab Berred, below Jbel Tizirène (figure 1).
126 This mountain shows a clear altitudinal zonation from evergreen oaks (*Quercus ilex*) on the lower
127 slopes, followed by deciduous oaks (*Q. canariensis* and then *Q. pyrenaica*) and *Cedrus atlantica* on
128 the very top of the mountain. The site is a floating bog surrounded by cultivated land and poplars
129 (*Populus* spp). In 2012, we collected a 650 cm core (ANS) at 35°01'3.4"N, 4°59'34.5"W, 1342 masl.
130 AMS ¹⁴C dates on four bulk sediment samples (table 1) provide a chronology for the last 2000
131 years.

132

133 **2. Dayet M'Had**

134 Dayet M'Had is located south of the Parc Naturel de Bouhachem at the westernmost part of
135 the Rif Mountains. The park, covering an area of about 90,000 ha, is a protected area with many
136 wetlands, peatlands, highly diverse forest stands and matorrals that provide habitat for rare animal
137 and plant species. The core site is currently surrounded by *Pinus halepensis*. Cedar forests occur at
138 a higher altitude about 4 km from the study site. In 2012, we collected a 550 cm core at 35°7'557"N,
139 5°26'455"W, 754 masl (figure 1). Five ¹⁴C AMS dates on bulk sediment (table 1) indicate that the

140 core covers the last 5000 years.

141 **B. The Middle Atlas records**

142 Besides the Rif, Morocco has three other large mountain chains: the Middle, High and Anti-
143 Atlas. They separate the Mediterranean and the Atlantic from the Saharan Desert. The Middle Atlas
144 (800-2800 masl) is composed of Permo-Triassic bedrock covered by formations ranging from the
145 Jurassic to the Paleogene (Dresnay, 1988; Herbig, 1988). It includes two structural and
146 geomorphological units, the folded and the tabular Middle Atlas, separated by the North Middle
147 Atlasic fault (Arboleya et al., 2004). Alkaline basalts of Quaternary age cover large areas
148 especially in the centre of the two units. Subsidence due to an intense fault network, together with
149 the karstification of dolomites (Martin, 1981; Hinaje & Ait Brahim, 2002), allowed the formation of
150 about twenty natural permanent or semi-permanent lakes (Chillasse and Dakki, 2004). The Middle
151 Atlas has mineral resources including iron, zinc, lead and copper (Newman, 2012).

152 In the Middle Atlas, Jurassic dolomitic limestone covers a large area, overlaid in turn by
153 Quaternary basalts. Under a subhumid climate, brown fersiallitic soils have developed from this
154 bedrock by weathering of carbonates. The alteration of basaltic rocks generates clay minerals,
155 especially phyllosilicates, providing silica, aluminium and iron to the geochemical sedimentary
156 record (Dekayir et al., 2005) through rainfall-induced allochthonous input of terrigenous fractions to
157 the sedimentary basins. An earlier study (Rhoujjati, 2007) using XRD analyses on lacustrine
158 sediments showed dominance of carbonates, especially detrital dolomite, followed by iron
159 hydroxides, inosilicates (alteration of basalt), tectosilicates (ie quartz) and phyllosilicates (silicate
160 of alumina) resulting from Triassic argillite leaching.

161 These geological patterns and their evolution through time have led to the deposition of
162 minerals exploited by human populations since prehistoric times (Akdin et al., 2011). Today, two
163 main polymetallic districts are exploited in the Middle Atlas. The extractions concern different
164 types of mineralization among which lead, zinc, silver, and gold in the district of Tighza and
165 sulphides of lead, zinc, iron and copper in the district of Elhamam at about 50 km SE and 10 km
166 North of Azrou city.

167 Today, the Middle Atlas has the most extensive forests of *Cedrus atlantica* in North Africa
168 occupying about 140,000 ha (Benabid, 1985). Other forest vegetation is composed of
169 sclerophyllous species such as *Olea europaea*, *Quercus ilex*, *Q. coccifera*, and *Pinus halepensis*.
170 The climate is temperate and humid with an annual rainfall between 600 mm and 1200 mm and an
171 average annual temperature of 10°C.

172

173 **1. Ras El Ma marsh**

6

174 In 2011, a 3m long core was collected from Ras El Ma (REM) marsh (33°28,419'N,
175 05°08,325'W, 1633 masl) (figure 1) using a Russian corer. The sedimentological sequence, from the
176 top of the core, consists of 120 cm of highly organic peat, 160 cm of compact clayey silt and 20 cm
177 of oxidized sand with limestone concretions. Eight radiocarbon ¹⁴C dates were obtained from
178 organic bulk sediments (table 1). The record covers the last 18,000 years (Nour El Bait et al., 2014)
179 but only the data of the last 3500 years are presented in the present paper.

180 The REM site is a wetland situated in the centre of the Middle Atlas, about 5 km south of the
181 city of Ifrane towards Azrou. The site is formed by a slight depression oriented south west - north
182 east at an altitude of 1633m asl. Annual rainfall varies between 860 and 1120 mm with peaks in
183 November-December and February-March. Snowfall is variable with an annual average snow cover
184 of 3 weeks/year. The surrounding vegetation is dominated by *Cedrus atlantica* mixed with
185 evergreen stands of *Olea europaea*, *Quercus ilex*, *Q. coccifera*, and *Pinus halepensis* as well as
186 xerophilous plants marked by the presence of herbaceous taxa (Asteraceae, Chenopodiaceae,
187 Caryophyllaceae, Liliaceae, Poaceae and Apiaceae).

188

189 **2. Lake Tifounassine**

190 Tifounassine is a small freshwater lake in the Middle Atlas, 40 km from Azrou on the road to
191 Midelt, about 9 km south of the village of Timahdit (figure 1). In 2013 we collected a 550 cm long
192 core (TIF) from Tifounassine (33°09'N, 5°06'W, 1913 masl). Ten AMS radiocarbon dates show that
193 the record encompasses the Holocene but only the last 2500 years are discussed in the present paper

194 The wetland itself is composed of three parts: a deep, permanent lake occupying a small
195 crater, then a larger but shallower spring-fed lake located to the south, often muddy and marshy;
196 and a large marshy zone, often dry throughout the year and used by livestock. The site is heavily
197 overgrazed and the surrounding vegetation develops only in the wetter areas, which support many
198 hydrophilous taxa such as *Typha*, *Myriophyllum spicatum*, *Nasturtium officinale*, *Phragmites*
199 *communis*, *Ranunculus aquatilis*, *Scirpus lacustris* and *Tolypella hispanica*. The average annual
200 precipitation is ca. 680 mm, mostly as snow which may persist on the upper hills until March. The
201 average monthly temperature varies between -2°C and 30°C in winter and summer, respectively.

202 ***Palaeoecological records of human impact: the historical context***

203

204 When human populations increased in Europe there was an expansion of pastoral and arable
205 land within areas that would naturally be forested, and an increase in the use of forest products such
206 as fuelwood and construction materials leading to an overall decline of the forest areas (Kaplan et

207 al., 2009). In the Mediterranean countries of North Africa, there are very few data that provide clear
208 evidence of such intensive and/or continuous human disturbance throughout the Holocene. In
209 northern Morocco, there is evidence that the first agricultural societies settled around 5500 BC in
210 the lowlands (Zapata et al., 2013). In effect, most of northern Africa has undergone a succession of
211 periods of deforestation and afforestation, or simply of abandonment, over at least the last three
212 millennia (Mercuri et al., 2011), probably restricted to areas at low altitude.

213

214 Past human disturbance in the pollen records from Morocco may be related to three types of
215 human activity: grazing of forests by domestic goats, sheep and cattle; the expansion of cultivated
216 lands; and by wood intake from the forests for fuel and construction, including industrial activity
217 (Mather et al., 1998). These activities may be identified in the records through:

- 218 1. reduction in arboreal taxa (oak, pines and cedars) which may be related to suppression of tree
219 regeneration by grazing, to clearance for cultivation, or to exploitation of wood for construction,
220 heating, and fuel for producing industrial energy;
- 221 2. the occurrence of plant taxa that are either used and/or cultivated by man such as cereals, vines
222 and olive trees, or ruderal plant taxa that often accompany human disturbances such as *Cistus*,
223 *Urtica*, *Plantago*, *Mercurialis*, *Rumex*, and *Asphodelus* (López-Sáez et al., 2003; Sadori 2011);
- 224 3. increased abundance of grass (Poaceae) pollen co-occurring with ruderal taxa and declining
225 arboreal abundance;
- 226 4. the co-occurrence of peak abundances of charcoal with pollen indications of disturbance;
- 227 5. the co-occurrence of geochemical and geophysical indicators of allochthonous input of sediment
228 from the site catchments with pollen indications of disturbance;
- 229 6. strong fluctuations in arboreal pollen which may express cycles of deforestation and
230 abandonment, followed by natural regeneration of the forest (cf. Iversen, 1973).

231

232 Pollen data allow reconstruction of the type of change, smooth or abrupt, that an ecosystem may
233 undergo through time. The palaeoecological signal of human impact on forest ecosystems is often
234 rapid and abrupt, especially where a settlements is close to the core site, thus allowing some
235 discrimination between anthropogenic disturbances and longer, more gradual natural changes,
236 except in the case of lightning-caused fires. Ancient DNA analyses, complementing the fossil
237 pollen evidence, may help to determine more precisely both the timing and the type of human
238 activities over the past thousands of years (Giguet-Covex *et al.* 2014). Modern DNA may also
239 provide indirect evidence about human uses of forest resources: for instance, chloroplast
240 microsatellites and isozymes have been used to show the potential effects of human impact vs.

241 natural evolutionary processes on the genetic diversity of *Cedrus libani* in in the eastern
242 Mediterranean (Fady et al., 2008).

243

244 The sedimentary records may also contain valuable information concerning the watershed and its
245 input of geochemical elements. The geological composition and the vegetation cover of the Rif
246 mountains (dolomite) and the Middle Atlas (basalt or dolomite; Arboleya et al., 2004) provide
247 different chemical elements and amounts into the site where the records were collected. The
248 palaeoecological records used in this study were retrieved at altitudes higher than 1500 m. Lakes
249 and wetlands naturally draw people to the water resources, so that even in the absence of
250 archaeological evidence for settlement, it is likely that some of the soil erosion and forest
251 disturbance evident in the sedimentary records may be directly attributed to human agency in the
252 local environment. In other cases, where sites were too remote or too high for long-lasting
253 settlement, the sequences may record disturbance at a predominantly regional scale through far-
254 travelled pollen, and via dust and elemental fallout from mining and metallurgical industry. Like
255 those known from other regions (Shotyk, 1996a, 1996b; Mighall et al., 2002; Bindler, 2006; Guyard
256 et al., 2007; Pompeani et al., 2015), the sediments are not from archaeological sites and cannot be
257 considered as direct records of human activity in Morocco since they do not derive directly from
258 human environments. Nevertheless, the biological and geological indicators they contain allow the
259 identification of provide continuous records of varying levels of industrial output, whereas
260 archaeological data tend to provide a more episodic, discontinuous record.

261

262 Prior to the Romans, Morocco was occupied by the Phoenicians. The ancient city of Lixus,
263 settled by the Phoenicians, dates back to the 7th century BC. In this area, it seems that
264 anthropogenic activities (fire and grazing) over the last 3500 years did not impact strongly on a
265 well-developed cork oak (*Q. suber*) forest (Damblon, 1991). After the fall of Carthage, northern
266 Morocco was annexed to the Roman Empire in 40 AD. Roman influence expanded into the Middle
267 Atlas, as Roman populations settled the town of Volubilis, near Meknes (figure 1), then the capital
268 of Morocco (called Mauretania at that time). Morocco remained a part of the Roman Empire until
269 429 AD when the Vandals displaced the Romans, who recovered it and then left several times.
270 Thus, after ca. 500 AD the Rif and the Middle Atlas mountains remained occupied by the
271 indigenous Berber inhabitants and the Byzantines until the arrival of the Arabs in 681 AD (Sadiki,
272 1997).

273

274 Previous palynological investigations of human impact in the Middle Atlas (Lamb et al.,
275 1991) and the Rif mountains (Reille, 1977) as well as those in the present study (figures 2, 3 & 4)
276 show a regression of the forest taxa after 1000 BC, which suggests an increase of the human uses of
277 the high-altitude forests. Impact of human populations on the forest ecosystems prior to 1000 BC
278 was probably minor since anthropogenic indicators are not dominant in the sedimentary record. The
279 early changes in the vegetation during the mid-Holocene are very probably related first to the
280 progressive installation of Mediterranean seasonality (Roberts et al., 2001; Jalut et al., 2009) and
281 then to the gradual increase of summer aridity as observed throughout the south-western
282 Mediterranean region (Peyron et al., 2013). This climate aridification allowed the expansion of true
283 Mediterranean elements such as *Olea*, *Pistacia* and evergreen oak forest (*Q. ilex*, *Q. coccifera*).

284
285 Our data suggest that human use of forest resources was less drastic prior to the expansion of
286 the Roman Empire throughout the whole Mediterranean region. In Morocco, pollen records from
287 both the Middle Atlas and the Rif mountains tend to confirm such strengthening of human activities
288 during the spread of the Roman Empire. As stated by Mather et al. (1998), the deforestation trend
289 expressed, particularly in the pollen records of Ras El Ma and Tifounassine in the Middle Atlas, is
290 coherent with the pattern observed by McEvedy and Jones (1978) and more recently simulated by
291 Kaplan et al. (2009) in a vegetation model that shows a clear decline since 1000 BC.

292
293 Forest degradation also led to the exposure and erosion of the soils. Calcium (Ca) content in
294 the sedimentary record shows an increase which is very probably related to the erosion of dolomite,
295 after the spread of the Romans in the eastern part of the Rif (figure 1, Anaasser) and later at its
296 western edge (figure 1, M'had). Treaties signed between the Berber populations in the Rif
297 mountains and the Romans (Taiqui and Cantarino, 1997) substantially reduced the Roman impact
298 on the landscape and their intensive use of the cedar and fir trees because the Berbers remained the
299 only users of their forests.

300
301 In the Middle Atlas, the increase of Cu, Zn and Pb at Tifounassine (figure 3) and Ras El Ma
302 (figure 4), combined with forest regression about 2000 years ago, may be related to the presence of
303 local metal industries for extracting lead, zinc and copper using the forest wood as a source of
304 energy. The name of the Middle Atlas town "Rsass" (in Arabic) means literally lead, showing the
305 importance of mineral extraction in the area, which may date back to the Roman period. The decline
306 of zinc, lead and copper in the Middle Atlas records after the 15th century seems to suggest that
307 Roman industrial activities ceased when they left the area. Similar changes related to the same

308 activities are observed in the south of France (Elbaz-Poulichet et al., 2011).

309

310 A major break in the landscape history is marked by the arrival of nomadic and semi-nomadic
311 Arab tribes (Ballouche, 2013). These tribes exploited the forest but did not re-establish the
312 industrial metallurgy as in the Roman period. In the Rif mountains the records of Pb, Zn and Cu do
313 not show any significant changes over the last 2000 years (Bouaissa, PhD unpublished data),
314 suggesting that the metal industry remained confined to the Middle Atlas.

315

316 These late Holocene human activities had an important impact on the surrounding landscapes, but
317 they may also have contributed to wider scale changes. At the local scale, they obviously affected
318 ecosystem composition, structure and potentially their long-term dynamics. At the same time, basin
319 catchments and their hydrology were also impacted by the reduction of forest cover through
320 increasing runoff and soil erosion. At the global scale, Ruddimann (2003) has argued that human-
321 related reduction of forest cover and the development of agriculture, especially rearing of goats,
322 sheep and cattle, may have contributed to the early increase of atmospheric CO₂ evident from polar
323 ice-core records. Although the North African forests are obviously much less extensive than those
324 of Europe, Asia, the Americas and tropical Africa, their reduction may have made a contribution to
325 the alteration of the global carbon cycle. However, some climate simulations, using transient
326 models, tend to show that early CO₂ emissions to the atmosphere were probably not significant
327 enough to have a clear impact on global climate (Pongratz et al., 2009).

328

329 In fact, there may be significant contrasts in the impact of human activities at different scales.
330 A general decline in forest cover across North Africa masks local-scale growth or regrowth of
331 forests. The *matorralisation* process during the last millennium in Morocco derives from the
332 intensification of land clearance and grazing pressure, as well as a high frequency of fires (Reille
333 1977, Damblon 1991, Lamb et al. 1991, McGregor *et al.* 2009). However, after the 11-13th centuries
334 AD, one may observe the local emergence of a new type of landscape that is poorly documented in
335 terms of vegetation history: dehesa-like agro-sylvo-pastoral determined parklands (Vicente & Ales,
336 2006; Ballouche, 2013). These original Mediterranean landscapes were then eradicated during the
337 late 19th and early 20th century by agricultural intensification, or through reforestation.

338 **Conclusions**

339 Although the palaeoecological data used in this study do not originate from archaeological
340 sites, they do provide direct and temporally continuous records of exploitation of forest, soil and

341 mineral resources, at regional and local scales. They allow us to infer human activity during the last
342 two millennia, from palynological and geochemical evidence. Forest disturbances had an impact on
343 the surrounding environment through soil erosion and therefore on the release and transport of
344 geochemical markers through the eco-hydrological systems. Analysis of these geo-indicators allows
345 detection of the timing and varying intensity of the environmental changes. In the Middle Atlas,
346 metals such as copper, lead and zinc were extracted by the Romans. Mining and smelting required
347 the use of energy, obtained from the forests which served as a fuel source.

348 Today, there are initiatives in Morocco to preserve the forest ecosystems in the Rif and the
349 Middle Atlas in delineated parks and reserves. Clearly, not all the forests are protected from grazing
350 and clearing, and there is ongoing deforestation for various uses of wood in many areas in Morocco.
351 Besides the parks and reserves, there are also forest areas that are protected simply with fences
352 where there is some good regeneration through natural re-sprouting and seedlings. Outside these
353 protected areas there is very little if any natural regeneration of the forests, and in many cases the
354 effects of the strong deforestation on soil degradation, with heavy erosion, is evident.

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365 **Figure captions**

366

367 **Figure 1.** Map of forest vegetation in the Rif and the Middle Atlas mountains, showing locations of
368 palaeoecological sites.

369

370 **Figure 2.** Arboreal pollen and calcium content of sediment cores from Anaasser (left) and M'Had
371 (right) in the Rif mountains, plotted against a calibrated radiocarbon timescale. Dated bulk sediment
372 samples are indicated by red stars.

373

374 **Figure 3.** Arboreal pollen, selected anthropogenic indicator pollen taxa, and metal element content
375 of a sediment core from Tifounassine, Middle Atlas, plotted against a calibrated radiocarbon
376 timescale. Dated bulk sediment samples are indicated by red stars.

377

378 **Figure 4.** Arboreal pollen, selected anthropogenic indicator pollen taxa, and metal element content
379 of a sediment core from Ras El Ma, Middle Atlas. Dated bulk sediment samples are indicated by red
380 stars.

381

382

383 **Table 1.** Radiocarbon dates from bulk sediment samples from four sites in the Middle Atlas (Ras el
384 Ma and Tifounassine) and Rif (M'Had and Anasser) mountains. ^{14}C dates were calibrated with
385 Calib 7.1 (Reimer et al. 2013) using the calibration data set intcal13.

386

387

Figure_1
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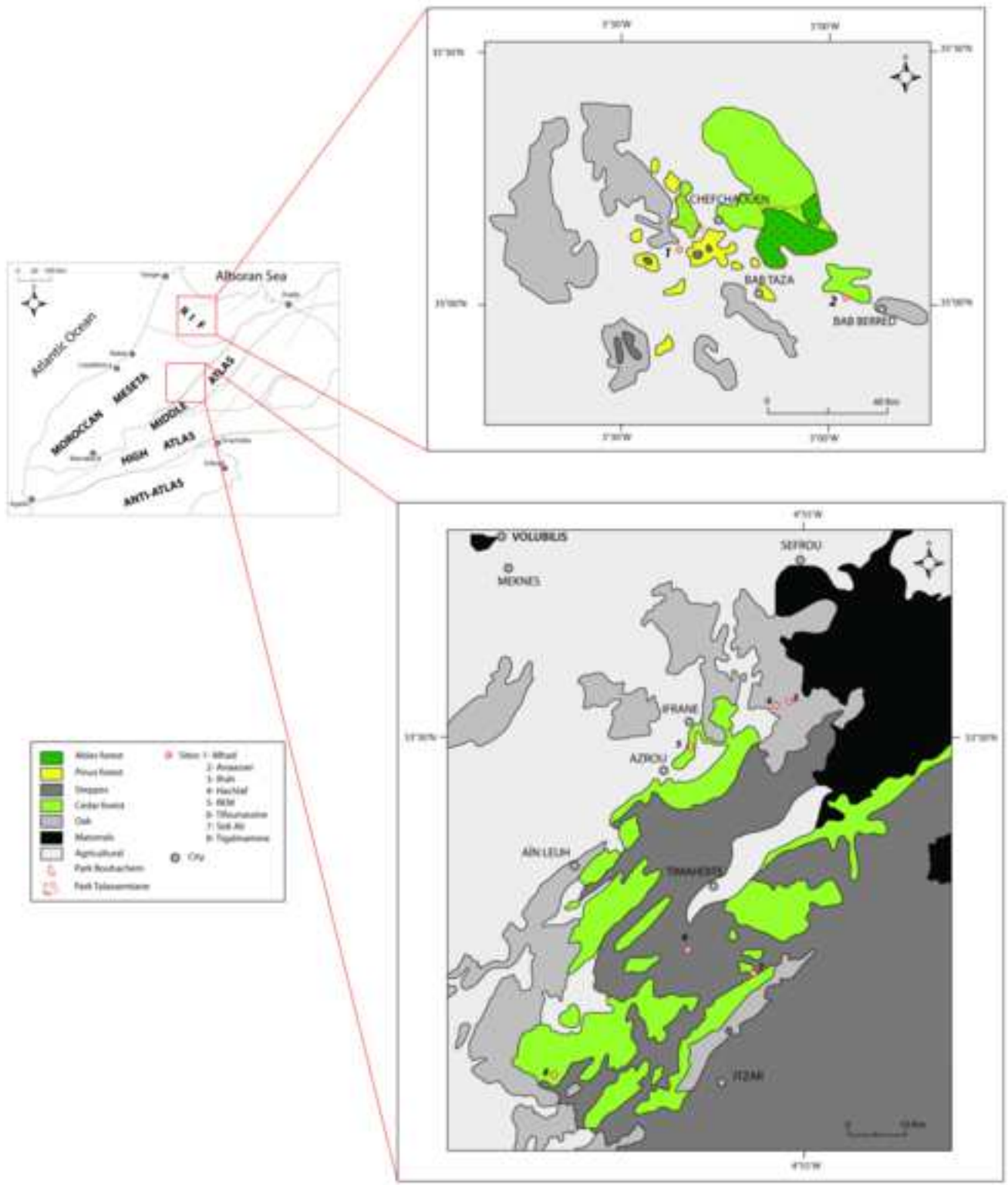
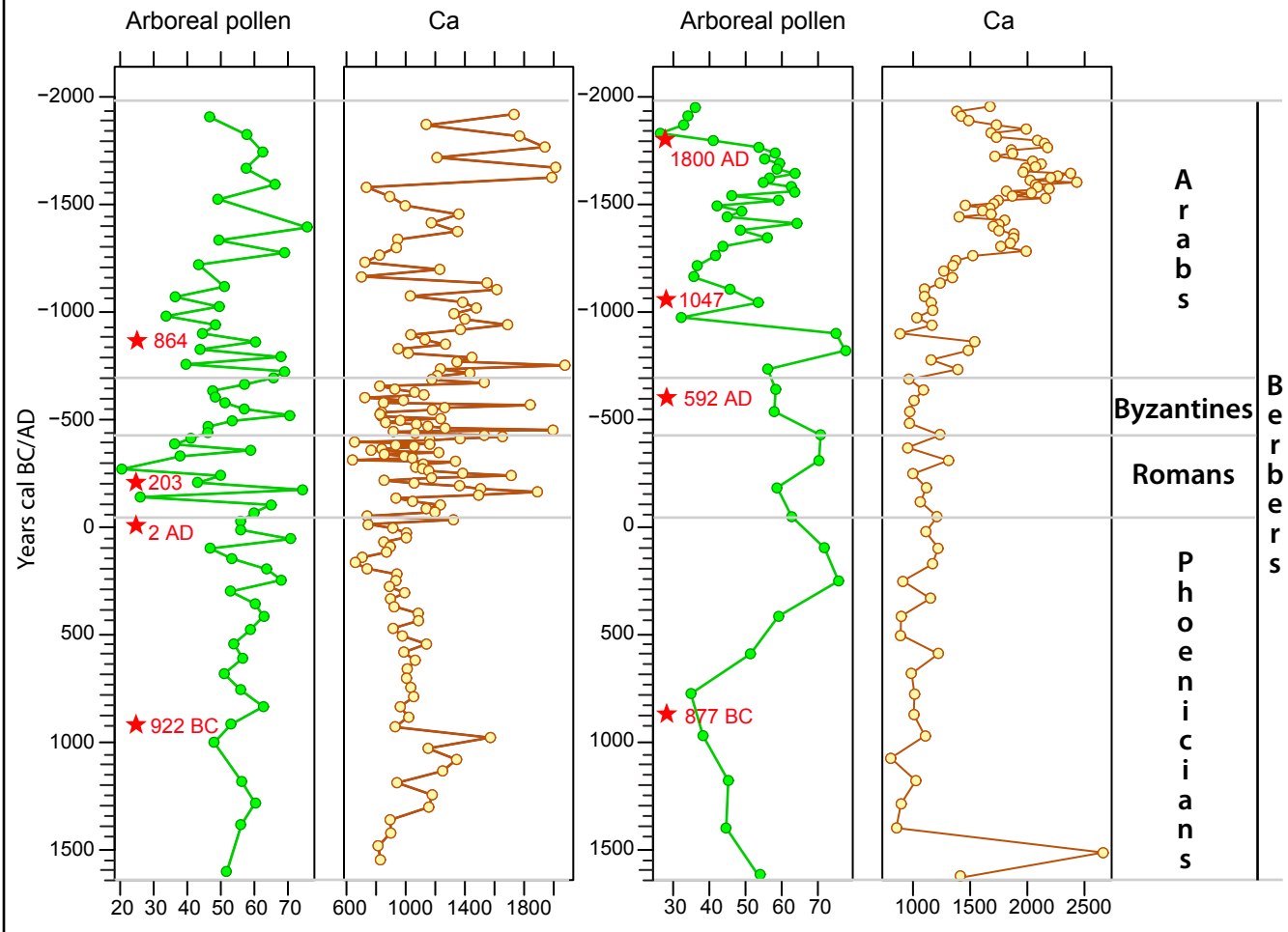


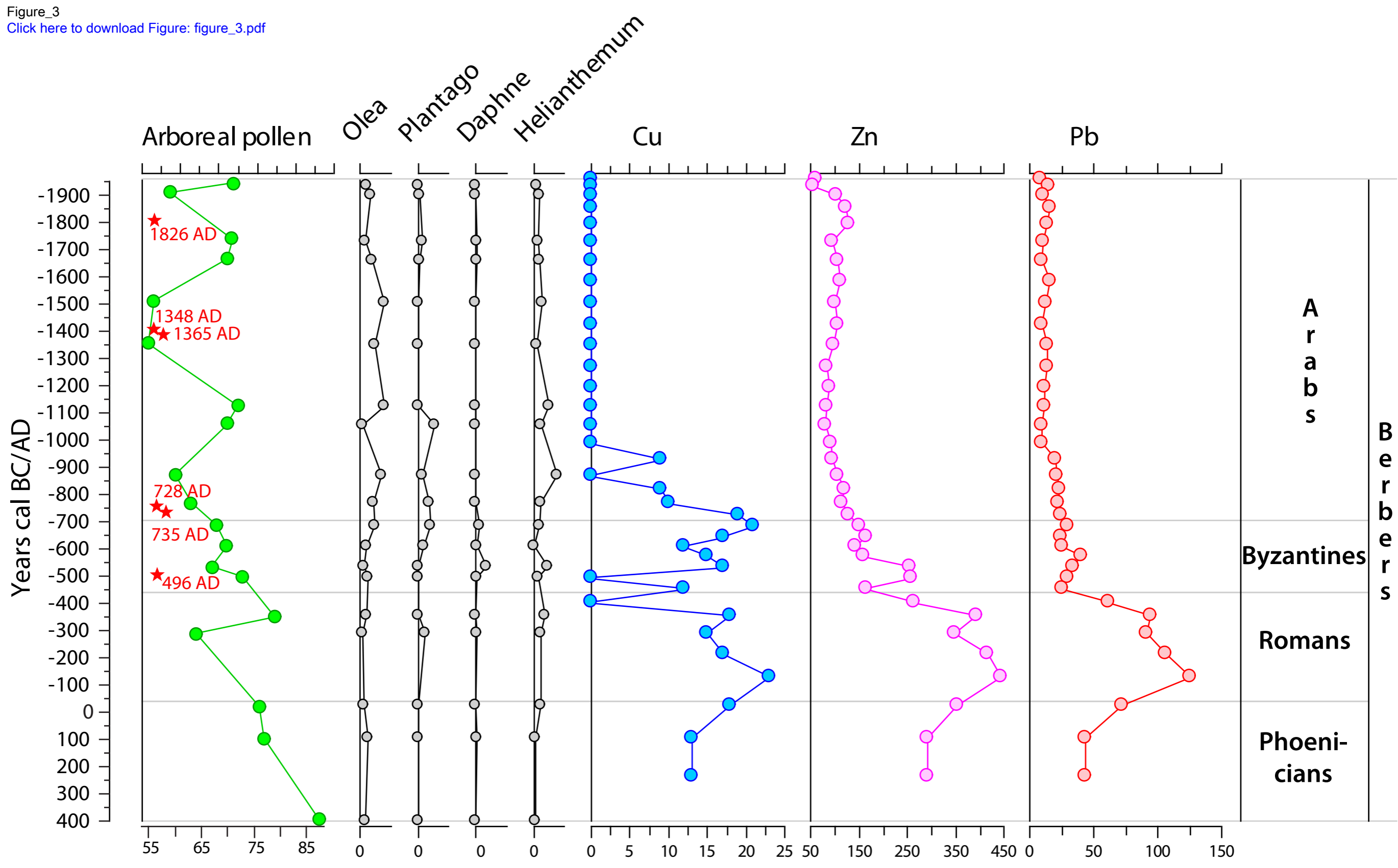
Figure 2
[Click here to download Figure figure_2.pdf](#)

Anaasser

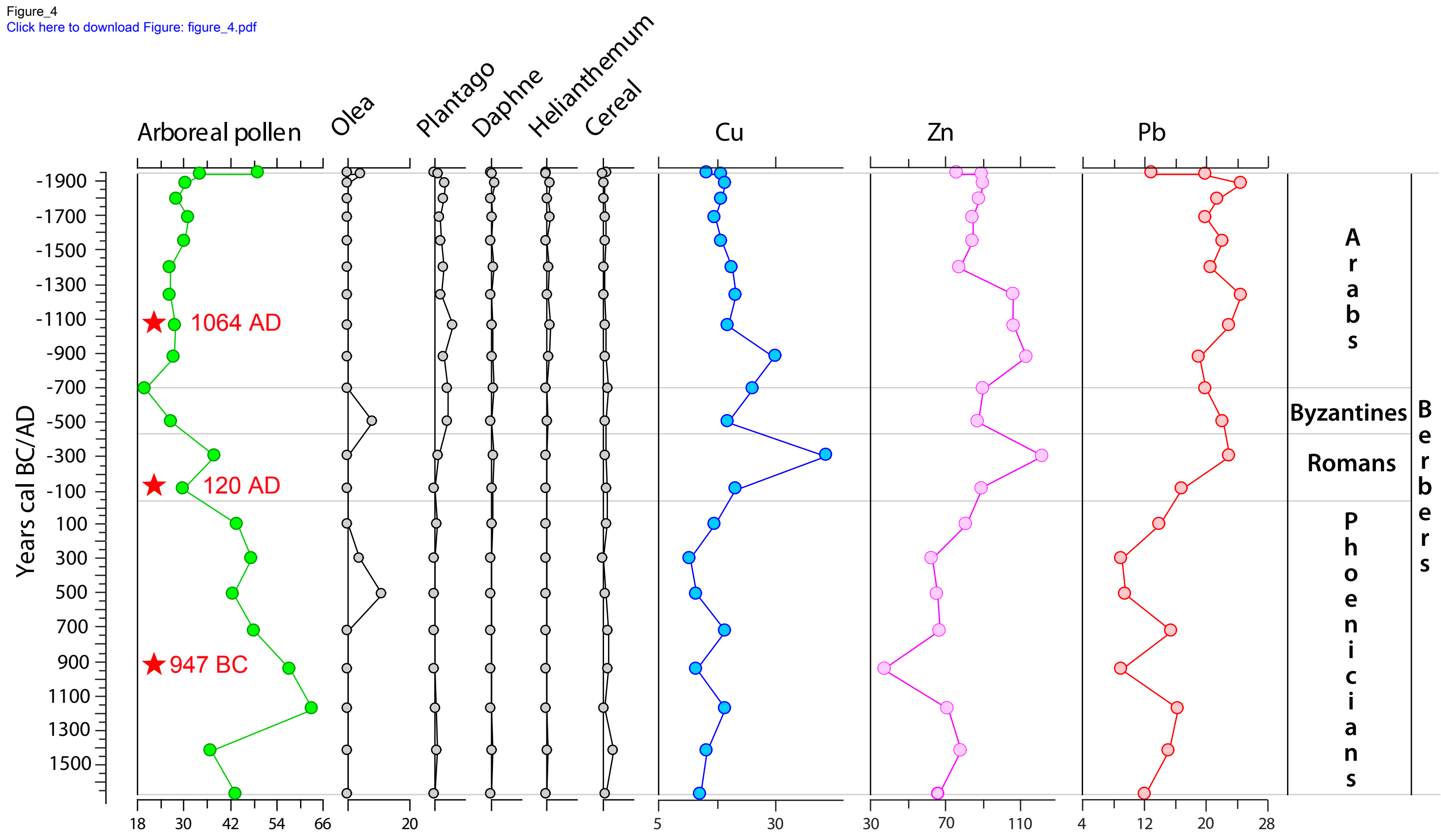
Mhad



Figure_3
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Figure_4
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Feuille2

| Site name | Lab number | Depth (cm) | ¹⁴ C yr BP | ¹⁴ C SD | Upper cal range BC/AD | lower cal range BC/AD | BC/AD median probability |
|---------------------|------------|------------|-----------------------|--------------------|-----------------------|-----------------------|--------------------------|
| Ras El Ma | Poz-44373 | 40 | 990 | 35 | 1154 | 987 | 1043 |
| | Poz-44374 | 95 | 1890 | 35 | 225 | 33 | 114 |
| | Poz-55269 | 116 | 2795 | 35 | -842 | -1025 | -947 |
| | Poz-44375 | 125 | 4190 | 40 | -2635 | -2894 | -2775 |
| | Poz-46161 | 137 | 4670 | 40 | -3363 | -3626 | -3452 |
| | Poz-46165 | 187 | 8290 | 50 | -7179 | -7488 | -7350 |
| | Poz-44377 | 210 | 12610 | 70 | -12621 | -13290 | -13013 |
| | Poz-44379 | 240 | 14690 | 90 | -15673 | -16163 | -15925 |
| Tifounassine | Poz-44380 | 7 | 117 | 10 | 1926 | 1688 | 1844 |
| | Poz-44481 | 42 | 620 | 35 | 1402 | 1290 | 1349 |
| | Poz-44382 | 57 | 565 | 30 | 1425 | 1306 | 1352 |
| | Poz-44383 | 92 | 1275 | 30 | 852 | 661 | 723 |
| | Poz-44384 | 112 | 1270 | 30 | 859 | 663 | 726 |
| | Poz-44385 | 132 | 1555 | 30 | 568 | 422 | 486 |
| | Poz-44386 | 153 | 2635 | 30 | -779 | -887 | -808 |
| | Poz-60034 | 180 | 3590 | 30 | -1884 | -2027 | -1944 |
| | Poz-60035 | 230 | 6490 | 35 | -5372 | -5515 | -5444 |
| | Poz-60036 | 330 | 10040 | 50 | -9361 | -9848 | -9596 |
| M'had | Poz-56679 | 65,5 | 155 | 30 | 1949 | 1666 | 1777 |
| | Poz-56680 | 278,5 | 995 | 25 | 1150 | 989 | 1028 |
| | Poz-56681 | 340,5 | 1475 | 20 | 637 | 554 | 592 |
| | Poz-56682 | 440,5 | 2735 | 30 | -814 | -968 | -873 |
| | Poz-56683 | 547,5 | 4980 | 35 | -3661 | -3927 | -3752 |
| Aanasser | Poz-54205 | 184,5 | 1165 | 30 | 966 | 773 | 860 |
| | Poz-54207 | 410,5 | 1810 | 35 | 329 | 93 | 203 |
| | Poz-54208 | 560,5 | 2000 | 30 | -54 | -83 | -70 |
| | Poz-54209 | 615,5 | 2775 | 30 | -842 | -999 | -920 |

Reply to reviewers

Reviewer #1:

1. The chronological framework of the sites appears to be robust. Details of the available radiocarbon dates should be listed in a table, with informations on the dated material, depths of samples, AMS ¹⁴C yr BP ages, etc...

A new table has been added, with dated samples from each fossil record.

I would also recommend not to mix uncalibrated and calibrated dates in the main text, to avoid confusion for those who do not feel comfortable with calibration curves. Following standard convention, uncalibrated dates should be reported as ¹⁴C yr BP, while calibrated dates should be reported as BC (or BCE).

All dates in the manuscript have been changed into either "¹⁴C yr BP" or "BC". "Uncal" or "cal" have been removed from the text. The time scale of all figures is now in BC/AD

2. The manuscript would benefit from some reorganization, moving most of the geological background in an expanded form of the site descriptions.

Thank you,

3. As REM, HAO1, TIF13 and Aït Ichou sites are presumably new unpublished sites, I strongly suggest that graphic logs, position of dated levels, main geochemical elements and summary percentage pollen diagrams be presented versus depth for each core. This would greatly help the reader to understand the type of changes that ecosystems underwent through time. A last figure displaying the synthesis of all data and the main cultural phases (Romans....) on a common time-scale would be appreciated.

The REM record is now published and properly cited (Nour El Bait, 2014). The publication contains detailed information about stratigraphy, age/depth model, detailed pollen and XRF data Aït Ichou and Hachlaf data have been removed since they are not being used in the discussion (we were expecting to obtain the XRF data in the meantime but we didn't manage it). Tifounassine (TIF13) extended data are being used in another publication in preparation which includes all detailed information. The inclusion of only a part of the data (the last 3000 years) in this publication is not suitable. In effect, all necessary information is now available in an improved version of figures 2, 3 and 4. Additional details would not bring more arguments for the discussion.

4. I was left wondering to what extent the paragraph about « Ruddiman's hypothesis » is useful and relevant in this paper. It should be cut in my opinion.

Instead of dropping that small paragraph, we have reworked it so that it fits the discussion.

Reviewer #2:

- Overall the background is good but this is occasionally marred by a lack of attention to detail which may be because the authors are unaware of geological studies. For example, it would be useful to include mention of the following new studies: Michard et al., 2006 on the geology of the Rif. Other recent works on the geology are uncited (pages 8 & 9) such as Michard et al., 2006.

Michard et al. (1998) deal mainly with the geological background of the Rif mountains. The publication is now properly cited

- The authors make the statement that minerals were exploited since prehistoric times (page 10 lines 3 & 4) without any reference from the literature.

A reference has been added:

- I found some of the chronological information a little hard to follow. For example, apart from Ras el Ma and Aït Ichou swamp there is no indication about the dated material and this could be more clearly explained in the text.

The point could also be made that the sites chronology is mainly based on AMS dating and that further work is required to explain briefly the dating method and whether it was the same as the one used for the previous work (Lamb et al., 1991). It would also be useful to mention the uncalibrated dates and the identification (if any) of the samples dated. Some mention of this should be made in the text.

Hopefully, this issue has now been (1) properly addressed in the manuscript, (2) a table with all dated samples has been added and (3) the dated samples are now plotted in red in each figure (2, 3 and 4).

- The description of the vegetation is straight-forward and clear and has been previously published but again some previous research on this topic are not cited (Benabid, 2000).

Thank you, indeed Benabid's work was unfortunately not cited. It is now

However, in addressing the human impact on the vegetation through time the authors propose new thoughts about the decrease of the forest cover and the increase of the geochemical markers based on relatively sparse evidence. While the authors show clearly the

forest reduction in both Rif and Middle Atlas, their interpretation of the lack of the Cu, Pb and Zn in the Rif can be challenged by the rare "important" Palaeozoic formations unlike the Middle Atlas.

We agree that the geological background of the Rif may be a good explanation to the low presence (and consequently low exploitation) of Cu, Pb and Zn

- The human impact on the vegetation should have been one of the central highlights of this paper but unfortunately the data are not presented in a way that would allow to understand it. Until now there is no clear archaeological evidence of the Roman presence in the Moroccan mountains including those of the eastern Rif and the Middle Atlas as it was published more than 25 years ago (Euzennat, 1989). The authors claim also that Morocco was occupied by the Phoenicians (page 13, line 1) and the understanding of this reviewer is that such presence was very limited to the coast. It might also have been valuable for the authors to have undertaken a research on the archaeological literature which is in this paper sadly very brief and uninformative.

We fully agree with these statements. However, as stated in the manuscript, the fossil pollen data do not allow to tackle archaeological issues. Thus, a thorough archaeological discussion is difficult to carry in such context.