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1 **Archaeomagnetic dating and magnetic characterization of ceramics from the**
2 **Paquimé, Casas Grandes region, Chihuahua, Mexico**

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22
23 **Abstract**

24 Casas Grandes is a prehistoric culture area located between Chihuahua, northern Mexico,
25 and New Mexico, southwest of United States of America. It had an intense occupation with
26 large buildings during the ceramic period, from 0 to 1450 AD, developing very particular
27 painted potteries. In this study, magnetic properties and archaeointensity experiments were
28 investigated on two special ceramic types called Mimbres and polychrome Ramos. They
29 come from four archaeological sites from Casas Grandes region in northern Chihuahua:

30 Paquimé, Villa Ahumada, Galeana, and Samalayuca. Archaeological timing and typology
31 assign Mimbres and Ramos to an age period between 900–1450 AD, but no absolute ages
32 are available. Magnetic properties show that Mimbres and Ramos have different
33 magnetomineralogical properties, suggesting that pottery making materials were different.
34 Mean archaeointensity results were obtained from nine different pottery sherds, five from
35 Mimbres and four from Ramos polychrome, for a total of 35 specimens. Intensity value range
36 from 49-59 μ T for Mimbres type and from 41-49 μ T for Ramos type. Archaeomagnetic dating
37 was performed using the SHAWQ2k global model and the Maghoub regional paleosecular
38 variation curve. Archaeomagnetic dating give an absolute age range of 960-1100 AD for
39 Mimbres type, and of 1300–1600 AD for Ramos samples, confirming that both ceramic types
40 were manufactured at different times. These results highlight the potential of
41 archaeomagnetism to precise the chronological framework of Casas Grandes culture.

42 Keywords: archaeomagnetism, ceramics, Paquimé, Casas Grandes, archaeomagnetic dating,
43 Mexico

44

45 **1. Introduction**

46 Archaeomagnetism is the magnetic study of different archaeological records, mainly baked
47 clays (e.g. kilns, hearths, ceramics). These baked materials contain ferromagnetic particles
48 (ca. 0.1% concentration) that acquire thermal remanent magnetization (TRM), parallel to the
49 direction (declination and inclination) of the ambient Earth's magnetic field (EMF) and
50 proportional to its intensity at the time of the last cooling. This TRM and hence the EMF
51 ancient direction (archaeodirection) and intensity (archaeointensity) remain preserved unless
52 another firing event occurred, or it was disturbed by lightning or chemical alterations for
53 example. In contrast to the ease of obtaining archaeodirection with a certain degree of
54 reliability, the archaeointensity estimation is still more difficult because the ferromagnetic
55 particles can have non-ideal magnetic properties as low thermal stability or large ($> 1 \mu\text{m}$)
56 multi-domain grain size. These non-ideal behaviours violate the fundamental conditions
57 needed to apply the most widely used archaeointensity method (Thellier & Thellier, 1959)
58 and its derivatives (Coe, 1967; Aitken et al., 1988; Tauxe and Staudigel, 2004).

59 The EMF is continuously changing in time, a phenomenon called palaeosecular variation
60 (PSV). If TRM data obtained from well-dated archaeological or igneous material have a
61 suitable spatio-temporal distribution, then the PSV can be described for any geographic
62 location by global spherical harmonic models, such as: ARCH10k.1 (Constable et al, 2016),
63 ARCH3k.1 (Korte et al., 2009), CALS10k.1b (Korte et al., 2011), CALS10k.2 (Constable et
64 al., 2016), SHA.DIF.14k (Pavón-Carrasco et al., 2014), COV-ARCH and COV-LAKE
65 (Hellio and Gillet, 2018), BIGMUDI4k.1 (Arneitz et al., 2019), and SHAWQ2K
66 (Campuzano et al., 2019). Also, regional PSV reference curves can be generated for a given
67 area, using full-vector (direction and intensity) (e.g. Kovacheva et al., 2014; Tema and Lanos,
68 2020), directional (e.g. Hagstrum and Champion, 2002), or intensity (e.g. De Marco et al.,
69 2008; Hervé et al., 2017) data. For Central Mexico, three regional curves of the geomagnetic
70 field intensity were recently generated (Goguitchaichvili et al., 2018a; Hervé et al., 2019;
71 Mahgoub et al., 2019a). The curves of Goguitchaichvili et al. (2018) and Mahgoub et al.
72 (2019a) were built using a bootstrap approach (Thébault and Gallet, 2010), but both curves
73 have different input and data selection strategies. Goguitchaichvili et al. (2018) curve was
74 constructed for the past 3000 years using intensity data previously published from Mexico
75 and Southern USA. An update of this curve has been recently released (García et al., 2020).
76 We note that some of the input data in these curves were corrected with a contested anisotropy
77 method (for details see Hervé et al., 2019). Mahgoub et al. (2019a) full-vector curve covers
78 the past 46 ka and was constructed from their data (Mahgoub et al., 2019b) as well as from
79 previous data published from Central Mexico, which were selected after application of strict
80 selection criteria and reassessment of previous ages. The intensity curve of Hervé et al.
81 (2019) was determined using a Bayesian method (Hervé and Lanos, 2018), with selection
82 criteria similar to those of Mahgoub et al. (2019a), but without the high-quality intensity data
83 of Mahgoub et al. (2019b). For northern Mexico, a PSV master curve has yet to be
84 constructed, although previous palaeomagnetic (e.g. Alva-Valdivia et al., 2019; Rodríguez-
85 Trejo et al., 2019b) and archaeological (Pails, 2017; Mathiowetz, 2019) studies showed the
86 wealth of this region with volcanic and archaeological materials.

87 The greatest benefit of PSV reference curves is that they can be used in archaeomagnetic
88 dating (Aitken, 1966; Eighmy and Sternberg, 1990; Sternberg, 2008). Archaeomagnetic
89 dating consists in the comparison of the direction and/or intensity of undated material with a

90 PSV reference curve (regional or global). This dating technique was successfully applied in
91 different regions over the globe, such as northwestern America (Hagstrum & Blinman 2010)
92 and Europe (e.g. Arrighi *et al.*, 2006; Schnepf and Brüggler, 2016; Tema *et al.*, 2019),
93 accordingly it can be used as an alternative to other traditional methods (e.g. radiocarbon and
94 thermoluminescence dating). In Mexico, previous studies have confirmed the validity of this
95 method with Holocene erupted lavas (e.g. Böhnelt *et al.*, 2016; Mahgoub *et al.*, 2017, 2018)
96 and also archaeological artefacts (e.g. Goguitchaichvili *et al.*, 2016; 2017), located in Central
97 Mexico. So far, no archaeomagnetic dating has been applied to the region of northern
98 Mexico.

99 In this study, magnetic properties and archaeointensity data are presented for two types of
100 potteries (Ramos and Mimbres) collected from four archaeological sites belonging to the
101 culture of Casas Grandes, Chihuahua, northern Mexico. These potteries were previously
102 catalogued by archaeologists as being of the Mimbres (designs black or red on white fund)
103 and Ramos (polychrome) types, with a global age period ranging from 900 to 1450 AD (Dean
104 & Ravesloot, 1993; Kelley & Phillips Jr., 2017; Ravesloot *et al.*, 1995; Stewart *et al.*, 2005;
105 Whelan & Minnis, 2009). The main objective of this study is to test the potential of
106 archaeomagnetic dating at this period in Northern Mexico.

107

108 **2. Archaeological setting**

109 The archaeological materials of this study are from the Casas Grandes and Mimbres cultures,
110 located at the northwest of Chihuahua (Mexico) and southwest of New Mexico (US),
111 respectively (Fig. 1). Both belong to the major culture called ‘Mogollon’ that, together with
112 ‘Pueblo Ancestral’ (before Anasazi) and ‘Hokoham’, constitutes the cultural macro-region
113 ‘Oasisamerica’ or ‘Aridoamerica’ (Kirchhoff, 1954).

114 Since many years, the Casas Grandes culture, and its capital Paquimé, has caught the
115 attention of specialists (Bandelier 1890; Brand 1943; Di Peso 1974; Kelley & Phillips Jr.,
116 2017; Lumholtz 1904; Sayles 1936; Whalen & Minnis, 2001, 2009). Chronological
117 framework of Casas Grandes culture was recently revised by Pailes (2017). Between 1959
118 and 1961, Charles Di Peso (Di Peso *et al.*, 1974) started a very intensive and rigorous
119 archaeological study in Paquimé, recovering large amount of potteries, shells, and organic

120 materials that allowed the first chronology of the region. He identified two important cultural
121 branches: pre-ceramic and ceramic.

122 **2.1 *Pre-ceramic Period***

123 This is a large period that starts ca. 12,500 BC, when the inhabitants were ‘hunters-gatherers’
124 in the Paleocene. This period is called ‘Paleoindio’ characterized mainly by the Folsom and
125 Clovis grooved arrows found in Chihuahua (Di Peso, 1965). After the Paleoindian period,
126 started the ‘Archaic’ period (9000 BC to 0), characterized by semi-nomadic life-style and the
127 appearance at the end of an early agriculture.

128 **2.2 *Ceramic Period***

129 This period is divided in four main phases:

- 130 1) The Plainware period (1 to 700 AD) corresponds to the first ceramic traditions, with
131 brown to red color pots, jars, and pipes without decoration.
- 132 2) The Viejo Period (700 to 1200 AD) corresponds to the establishment of Paquimé city
133 with related settlements in surrounding caves. This period is divided in two phases:
134 Early Viejo and Late Viejo (Dean & Ravesloot, 1993; Kelley & Phillips Jr., 2017;
135 Ravesloot et al., 1995; Stewart et al., 2005; Whalen & Minnis, 2009). At the end of
136 this period appear evidences of exchange with other cultures from Central and
137 northern Mexico as well as southwest of United States, with many shells, turquoise
138 counts and cooper artifacts.
- 139 3) The Medio Period (1200 to 1450 AD) corresponds to the full development of the
140 Casas Grandes culture. Paquimé has grown with a strong increase of the population,
141 the development of economy, politics, social and culture, and the maximum
142 architectural magnificence. One of the most conspicuous features of this period in the
143 Casas Grandes region is a remarkable polychrome ceramic, with thinner textures, and
144 a variety of sophisticated designs with anthropomorphic and zoomorphic shapes.
- 145 4) The Late Period corresponds to the start of the waning of Paquimé (Di Peso, 1974).

146 **2.3 *Sampled potteries***

147 24 sherds were collected by R. Cruz-Antillón at the surface of different sites in the Casas
148 Grandes region: Paquimé, Galeana, Villa Ahumada and Samalayuca (Fig. 1, Table 1). This
149 work was intended as a pilot study to test the efficiency of archaeomagnetic dating for this

150 ceramic type. If the results are positive, the archaeomagnetic dating technique could be
151 applied to other sherds of this region for which the stratigraphy between archeological
152 layers is not well defined and no other dating is possible.

153 The sherds were classified accordingly to their typology (Mimbres and Ramos
154 polychrome), characterized by designs unique in the region (Fig. 2). The Mimbres ceramic
155 belongs to the period 1000 to 1150 AD and is distinguished by its white color and motifs
156 painted in black, generally jars. The Ramos polychrome ceramic is characterized by matte
157 cream-orange decors with red and black color, and very eccentric shapes. This ceramic is
158 typical of the Paquimé Medio period between 1200 to 1450 AD.

159

160 **3. Laboratory procedures**

161 We first performed thermomagnetic experiments with the recording of susceptibility (k) as a
162 function of temperature, the so-called k - T curves. Representative samples were heated in air
163 up to 600-700°C with a MFK-FA susceptibility-meter (Agico, Kappabridge) and then cooled
164 back to room temperature. Curie temperature (T_c) value(s) and the type of the ferromagnetic
165 minerals were investigated from these curves, as well as the thermal stability of the samples.
166 We measured the hysteresis properties and the isothermal remanent magnetization (IRM)
167 spectra, by using a Princeton AGFM Micromag 2900 apparatus, in fields up to 1.2 Tesla at
168 room temperature. From them, saturation magnetization (M_s), saturation remanent
169 magnetization (M_{rs}), coercive force (H_c) and remanent coercive force (H_{cr}), were determined.
170 The ratios of these parameters provide rough information on the size distribution of the
171 magnetic domains and the different mixtures of magnetic minerals contained in the samples
172 (e.g., Day et al., 1977; Dunlop, 2002).

173 One specimen per sherd, cut on parallelepipedic shape of *ca.* 18×5×3 mm, was thermally
174 demagnetized (ThD) to investigate the number of remanent magnetization components and
175 to define the unblocking temperature ranges. Three to six specimens of each sherd were used
176 for archaeointensity experiments using the Thellier & Thellier (1959) classical double
177 heating method. The Thellier & Thellier (1959) method involves heating a specimen twice
178 with a laboratory-induced magnetic field applied along its two long axes (+ z , - z). Heating
179 was done from 150 to 580 °C with 10 to 12 steps, and the laboratory field was set to 40 μ T.

180 During the experiments, partial thermal remanent magnetization (pTRM) checks (Coe, 1967)
181 were performed every two temperature steps to check for magneto-mineralogical alteration.
182 The stepwise heating-cooling process was performed using a MMTD24 oven, and the
183 remanent magnetization was measured with a JR6 spinner magnetometer. Results were
184 processed with the ThellierTool 4.22 software (Leonhardt et al., 2004). In order to accept
185 archaeointensity results, the following quality criteria were considered: 1) Number of steps
186 (N) used to calculate the best-fit linear segment on Arai plot (Nagata et al., 1965) higher or
187 equal to 5; 2) Ratio (β) of the standard error of the slope of the best-fit line to the absolute
188 value of the slope lower than 0.15; 3) NRM fraction (f) greater than 30%; 4) Gap factor (g),
189 that reflects closeness of points along Arai plot segment selected for intensity determination
190 (Coe et al., 1978) higher than 0.5; 5) Quality factor ($q=fg/\beta$) higher than 3; 6) Anchored
191 maximum angular deviation (MAD_{anc} ; Kirschvink, 1980) lower than 15° ; 7) Angular
192 difference (α) between the anchored and the non-anchored best-fit directions lower than 15° ;
193 8) Relative check error (dCK), defined as the maximum difference produced by a pTRM
194 check normalized to the TRM, lower than 10%; and 9) Cumulative pTRM check (dpal; Valet
195 et al., 1996) lower than 15%. In order to calculate a mean archaeointensity at the sherd level,
196 at least 3 specimens must be accepted, and the standard deviation (σ) should not exceed 6
197 μ T. The current selection criteria are similar to sets proposed in other studies, e.g. SELCRIT2
198 (Biggin et al., 2007) or ThellierTool B (TTB) (Leonhardt et al., 2004).

199 Ceramics manufacturing process commonly results in preferential alignments of the
200 magnetic grains inducing a TRM anisotropy effect, and this anisotropy has been shown to
201 bias the archaeointensity estimates (Rogers et al., 1979; Aitken et al., 1981). Therefore, it is
202 necessary to correct for this effect by calculating the anisotropy tensor of TRM (Veitch et al.,
203 1984; Chauvin et al., 2000) with six successive heating at 540°C along 6 positions (+x, -x,
204 +y, -y, +z and -z specimen axes), followed by a stability check. The influence of cooling
205 rate on TRM intensity was tested with the procedure described in Chauvin et al. (2000). The
206 duration of the slow cooling was fixed to 5 hours due to experimental constraints, in
207 comparison with the rapid cooling that took *ca.* 45 min. It is worth pointing out that this
208 duration is close to the one provided by experimental archaeology of ceramic production in
209 the American Southwest (Jones-Cervantes et al., 2020).

211 4. Results

212 4.1 Magnetic properties

213 The heating-cooling branches of the k-T curves are shown in Figure 3. According to the T_c
214 values and the degree of reversibility between the heating and cooling curves, samples could
215 be classified into three groups. The first group, which include all sherds of Ramos type, has
216 a single high T_c ranging between 500–580 °C (Fig. 3, PR-2, GR-4, and VAR6),
217 corresponding to a typical behaviour of Ti-poor titanomagnetite (TMag) and/or magnetite
218 (Mag). This group shows a good degree of reversibility indicating thermal stability at high
219 temperatures. The second group of samples is also characterized by a single high T_c ranging
220 from 500–540°C (Fig. 3, CH-3-3, and PM-2) but irreversible curves with the cooling curve
221 rising above the heating curve. The interpreted magnetic mineralogy content of this group is
222 mostly Ti-poor TMag, which transforms after heating to 700 °C in TMag with less Ti and a
223 higher magnetic content. The third behaviour, seen solely in sample PM-1 (Fig. 3), shows
224 two T_c points: the first is ~340 °C while the second T_c ranges from 480 to 560 °C, suggesting
225 coexistence of Ti-poor and Ti-rich TMag (the last one probably created during the
226 experiment). This group is characterized by low degree of reversibility with a large increase
227 of the susceptibility after heating to 700 °C. Samples of this group were not used for
228 archaeointensity experiments. It must be noted that all investigated samples of Ramos belong
229 to the 1st group while the 2nd and 3rd group samples are from Mimbres pottery types.

230 The hysteresis curves (Fig. 4) present two different shapes indicating diverse mixtures of
231 magnetic mineralogy. The '*potbellied*' shape, observed in 65% of the samples (e.g. Fig. 4:
232 CH-3-1-4, CH3-3-2, VAR-10 and GR-4), shows a typical pseudo single-domain (PSD)
233 behaviour with smaller magnetic grain size (see Fig. 5, Tauxe, et al., 1996, 2002). Other
234 specimens (e.g. Fig. 4: PM-1 and PR-2) present 'wasp-waisted' hysteresis curves,
235 highlighting a mixture of low and high coercivity magnetic minerals, such as titanomagnetite
236 and minor amount of titanohematite. This mixture shows a trend of superparamagnetic (SP)
237 (Tauxe et al. 2002) and larger PSD-like to multidomain (MD) grains. Both shapes can be
238 observed in Mimbres and Ramos polychrome. The larger differences between hysteresis
239 curves before and after the paramagnetic correction shows that the contribution of
240 paramagnetic minerals is higher for specimens PR-2 and CH-3-3-2. Inset in each graph of

241 Figure 4 are the IRM and backfield curves, where the contribution of magnetic components
242 and possible composition can be identified from the saturation magnetization and coercivity
243 values. All samples are dominated by a magnetic component with coercivities below 200-
244 300 mT that corresponds to the Ti-poor titanomagnetite seen in the k-T curves. A high
245 coercivity component, likely titanohematite, is also present in variable proportion. In
246 agreement with hysteresis results, the highest proportion is observed in PM-1 and PR-2
247 samples.

248 Result of hysteresis parameters and ratios are listed in Table 2 and plotted on a Day plot (Day
249 et al., 1977) in Figure 5. This diagram is commonly used to identify the size of the
250 ferromagnetic particles (single-domain SD, pseudo-single domain PSD, multidomain MD,
251 and superparamagnetic SP particles), when the magnetic carriers are only magnetite grains.
252 Here, the presence of a high-coercivity component shifts the specimens, especially PM-1 and
253 PR-2, to the right of the Dunlop (2002) curves. If this prevents to accurately determinate the
254 particle sizes, the Day plot remains relevant to discriminate between the different pottery
255 types, Ramos polychrome being slightly lower than Mimbres samples in the PSD zone.

256 **4.2 Archaeointensity**

257 Archaeointensity experiments were performed on 16/24 pottery sherds, eight from Mimbres
258 and eight from Ramos polychrome ceramic types. These sherds were selected because they
259 exhibit a single component of thermoremanent magnetization and reversible k-T curves.

260 The thirty-six specimens (10 out of 16 sherds) that fulfil the acceptance criteria are listed in
261 Table 3, and representative Arai plots are shown in Figure 6. Archaeointensity statistical
262 parameters indicate that the obtained results are of good quality (Table 3).

263 The TRM anisotropy (ATRM) correction was applied to all accepted archaeointensities and
264 resulted in a decrease of the values by *ca.* 1% to 4%. The cooling rate (CR) effect was tested
265 on eight specimens from PM-2 and PR-1 samples. As correction factors were pretty small
266 and very similar (between 3.4 and 4.9%), an average value of 4% was applied to all accepted
267 anisotropy-corrected archaeointensities. Table 3 lists raw, corrected for ATRM and for CR
268 effects estimates (F_{raw} , F_{ATRM} and $F_{\text{ATRM+CR}}$, respectively).

269 Mean archeointensity estimates could be calculated for nine sherds that have at least three
270 accepted specimens. The application of ATRM and CR corrections generally decrease the

271 standard deviation (Table 3), and the archaeointensity ranges for the Mimbres and Ramos
272 ceramic types are between 49–59 μT and 41–49 μT , respectively. These ranges support
273 cooling at different periods. This study reports the first high quality archaeointensity data for
274 northern Mexico.

275

276 **4.3 Archaeomagnetic dating**

277 Archaeomagnetic dating consists in the comparison of direction and/or intensity, obtained on
278 a lava flow or an archaeological artefact of unknown age, with a reference PSV curve
279 generated from a set of well-dated materials. The dating procedure is done by integrating,
280 with a certain confidence level, probability density functions that obtained from comparing
281 EMF elements (declination, inclination, or intensity) with their counterparts in the reference
282 curve. Combining the density functions produces a unique date or a set of possible dates. For
283 the latter, the most likely age may be assigned by using some independent details from the
284 stratigraphic or archaeological background. In this study, the integration is done for intensity
285 data, at a 95% confidence level. We used the MATLAB *archaeo_dating* software (Pavón-
286 Carrasco et al., 2011). As the proposed archaeological age period for Mimbres and Ramos is
287 900–1450 AD, we restrict the dating analysis to 500-1600 AD.

288 In Mexico, as well as in American Southwest, most intensity data present in databases such
289 as GEOMAGIA50 cannot be considered of high quality with our current quality standards
290 (Hervé et al., 2019; Mahgoub et al., 2019a; Jones-Cervantes et al., 2020). That's why we
291 choose to use the regional curve of Mahgoub et al. (2019a), and the SHAWQ2k global model
292 (Campuzano et al., 2019) that both were built with a quality selected dataset. From here, we
293 will refer to SHAWQ2k and Mahgoub curves as global and regional curves, respectively.
294 Both curves have been generated at the coordinates of Mexico City (19.43° N, 99.13° W) and
295 all archaeointensities have been also relocated there (Table 3), through virtual axial dipole
296 moment (Creer et al., 1983). Of course, the regional and global curves could also have been
297 relocated to Paquimé coordinates, however, we choose not to implement that option because
298 of the absence of intensity data in northern Mexico.

299 The archaeomagnetic age ranges for each sherd (five for Mimbres and four for Ramos
300 polychrome) are summarized in Table 4. Typical examples obtained with the regional and

301 global curves are presented in Figure 7 for each pottery type, and all archaeomagnetic dating
302 with the regional curve are listed in the supplementary material. The regional and the global
303 curves give very different age ranges (Table 4) but clearly those obtained with the regional
304 curve are in much better agreement with archeological estimations (1200-1450 AD for
305 Ramos and 1000-1150 AD for Mimbres). For Mimbres, regional-based age ranges are
306 usually pretty tight except for one sherd (VAM4, Figure 8), that gives a much larger range
307 because of its bimodal distribution (supp. material). Privileging the first mode makes the age
308 range for Mimbres much shorter, between 960-1100 AD. For Ramos, the age ranges are
309 slightly wider but in agreement between 1300-1600 AD.

310

311 **5. Discussion**

312 The precision of the obtained archeomagnetic ages depends on several factors, including (1)
313 the fidelity of the archaeointensity results; (2) the used reference curve; and (3) the relocation
314 approach. The archaeointensity data (Table 3) is of good quality after the anisotropy of
315 ATRM correction to all specimens. The cooling rate effect, however, could not be estimated
316 for each specimen and rather an average cooling-rate correction factor of 0.96 (estimated on
317 a few numbers of specimens from both Ramos and Mimbres types) was applied to all
318 specimens. We think that this limitation has little impact on our dating results.

319 Regarding the reference curves, archaeomagnetic dates derived from SHAWQ2k global
320 model (Campuzano et al., 2019) significantly differ from those obtained with Mahgoub et al.
321 (2019a) regional curve, the latter being more consistent with the archaeological context
322 (Table 4). The inaccuracy of SHAWQ2k model is likely attributed to the fact that it includes
323 Mexican intensity data without a reliable TRM anisotropy correction and without the cooling
324 rate correction, which yields to an overestimation of the geomagnetic field strength (Hervé
325 et al., 2019). In comparison, Mahgoub et al. (2019a) curve was constructed with a stricter
326 data selection, with more high-quality data (e.g. their new dataset) and after a revision of the
327 age of some previous data.

328 The precision of the relocation process depends on the magnitude of the non-dipole field
329 between Central and northern Mexico, but cannot be evaluated at that moment due to the lack
330 of intensity data in northern Mexico. According to Casas and Incoronato (2007), 1000 km

331 relocation can introduce an error of 1.5 μT on average. We do not insert an error to the
332 relocated intensity values (Table 3), as we do not have precise information on the
333 characteristics of the non-dipole field due to the lack of high-quality data in Mexico and the
334 USA. After comparing the intensity curve for Central Mexico with southern USA curve,
335 García et al. (2020) argued that non-dipole field between the two regions was small for the
336 past two millennia. We cannot evaluate this suggestion for the moment, but it should be
337 pointed that the data selection strategy used by García et al. (2020) includes data that were
338 not considered of sufficient quality in previous studies (Hervé et al., 2019; Mahgoub et al.,
339 2019a, 2019b; Jones-Cervantes et al., 2020).

340 Despite the mentioned uncertainties, archaeomagnetic dating was clearly able to discriminate
341 between Mimbres and Ramos types and will then be extremely useful to precise the
342 chronology of other not so easily identified sherds. We therefore recommend their use for
343 future archaeological studies on the Casas Grandes culture. Obviously, new high-
344 quality/well-dated palaeomagnetic data from northern Mexico will improve further the
345 precision of the archaeomagnetic dating.

346

347 **6. Conclusions**

348 The reported archaeomagnetic results show that the magnetic and archaeointensity
349 experiments can be used as proxies to differentiate between the Mimbres and Ramos ceramic
350 types. Both sherd types were collected from four archaeological sites from Pre-Hispanic
351 culture of Casas Grandes region: Paquimé; Villa Ahumada; Galeana; and Samalayuca, which
352 has global archaeological age of 900–1450 AD. The archaeointensity values for Mimbres
353 and Ramos types range between 49-59 μT and 41-49 μT , respectively. The difference
354 between the archaeointensity values clearly demonstrates the non-contemporaneity of the
355 two ceramic types. For dating purpose, the archaeointensity values were compared to global
356 and regional secular variations curves for Central Mexico. Archaeomagnetic dating results at
357 95% of confidence are 960-1100 AD for Mimbres type and 1300-1600 AD for Ramos
358 polychrome type. These dates are consistent with the archaeological context. Interestingly,
359 the different magnetomineralogical properties of Mimbres and Ramos sherds indicate that
360 the raw clay materials and probably the baking tradition used in the manufacturing process

361 were different at the two periods. This study confirms the ability of archaeomagnetism to
362 date displaced archaeological materials in Central America and of rock magnetism to
363 characterize and differentiate archaeological materials.

364

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372

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648

649 **Figure caption**

650

651 Figure 1. Location map of the sampling area shows Casas Grandes cultural region (pink area)
652 and studied archaeological sites (red points).

653

654 Figure 2. Representative sample sherds from this study in the Casas Grandes region: Ramos
655 polychrome, PR and Mimbres, PM. On the right, is shown typical example of Ramos
656 polychrome (above, Parada-Carrillo, 2016) and Mimbres pottery (below, Isabella, J., 2013);
657 scale is 30 cm wide.

658

659 Figure 3. Representative k-T curves of Ramos polychrome and Mimbres ceramic types from
660 the distinct localities. In each graph, the calculated Curie temperature is indicated as circle.

661

662 Figure 4. Representative hysteresis curves from the different localities before and after
663 subtraction of the paramagnetic components (in red and blue respectively). IRM and
664 backfield curves are in the inset of each graph.

665

666 Figure 5. Day plot of samples from Ramos polychrome and Mimbres ceramic types with SD-
667 MD mixing curves of Dunlop (2002).

668

669 Figure 6. Representative archaeointensity results with Arai plots to the left and orthogonal
670 vector plots to the right. NRM vs. pTRM data are shown as red circles, with best-fit lines
671 marked in dashed blue lines. pTRM checks are shown as triangles and some temperature
672 steps are also indicated. Orthogonal vector plot: Black and white circles represent the
673 projection of the magnetic vectors on the horizontal and vertical plane, respectively. Labels
674 along curves denote the temperature steps during the intensity experiments

675

676 Figure 7. Typical archaeomagnetic dating results for Mimbres (a, b) and Ramos polychrome

677 (c, d) ceramic types using the regional (a, c) and global curves (b, d). The comparison of the
678 average archaeointensity relocated to Mexico City with the curves provides the probability
679 density function, on which are defined the intervals of date at 95% of confidence. * Selected
680 interval according to the archaeological context.

681

682 Figure 8. Summary of archaeomagnetic dating results obtained with the regional curve for
683 Mimbres and Ramos. The location of the diamonds on the range corresponds to the maximum
684 of the probability distribution.

685

686 **Table caption**

687

688 Table 1. Location of the archaeological sites and acronyms of the sampled sherds

689

690 Table 2. Hysteresis parameters obtained in this study. M_{rs} , saturation remanent
691 magnetization; M_s , saturation magnetization; H_c , coercive force; H_{cr} , remanent coercive
692 force; M_{rs}/M_s , remanence ratio; H_{CR}/H_C , coercivity ratio.

693

694 Table 3. Summary of the archaeointensity results, obtained at specimen, sherd and pottery
695 type levels.

696 Specimen name, locality and type; N: Number of temperature steps included in the best-fit
697 line; f: NRM fraction; g: Gap factor; q: Quality factor; β : ratio of the standard error of the
698 slope of the selected segment in the Arai plot to absolute value of the slope; d(CK): relative
699 check error; d(Pal): cumulative check difference; α : angular difference between anchored and
700 non-anchored best fit direction; MAD_{anc} : anchored maximum angular deviation; $F_{raw} \pm \sigma_F$:
701 raw archaeointensity value with its standard deviation, calculated at each corresponding
702 archaeological site coordinates (see Table 1); F_{ATRM} : archaeointensity values corrected for
703 anisotropy of thermal remanent magnetization; $F_{ATRM+CR}$: archaeointensity value calculated
704 after anisotropy and cooling rate corrections (4% cooling rate factor is constantly applied to
705 all specimens); F (at C. Mexico): archaeointensity value relocated to Mexico City (19.43°N;

706 99.13°W); VADM: virtual axial dipole moment. Relocated F and VADM are calculated from
707 corrected archaeointensity values.

708

709 Table 4. Archaeomagnetic dating results obtained with regional curve for central Mexico
710 (Mahgoub et al., 2019a) and with the prediction of intensity values of SHAWQ2k global
711 model (Campuzano et al., 2019).

Figure 1

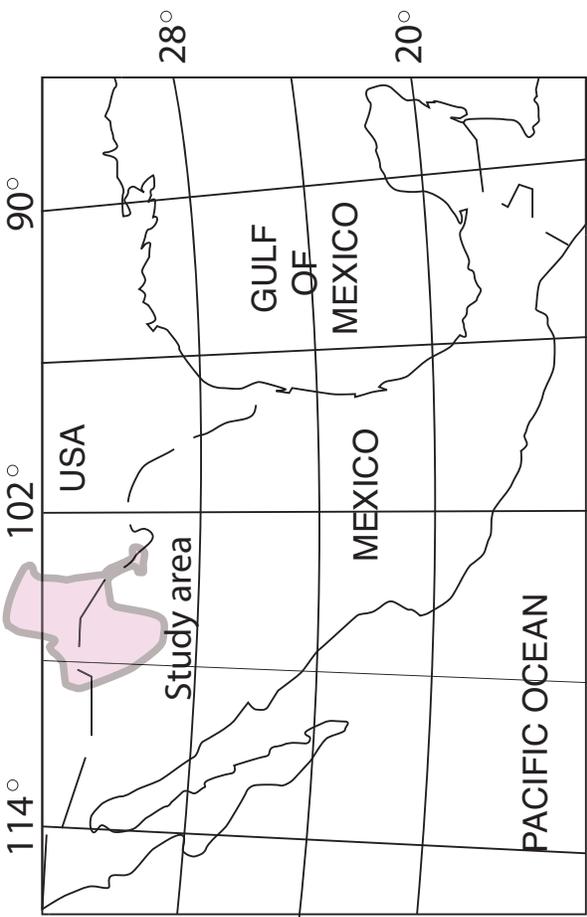


Figure 2

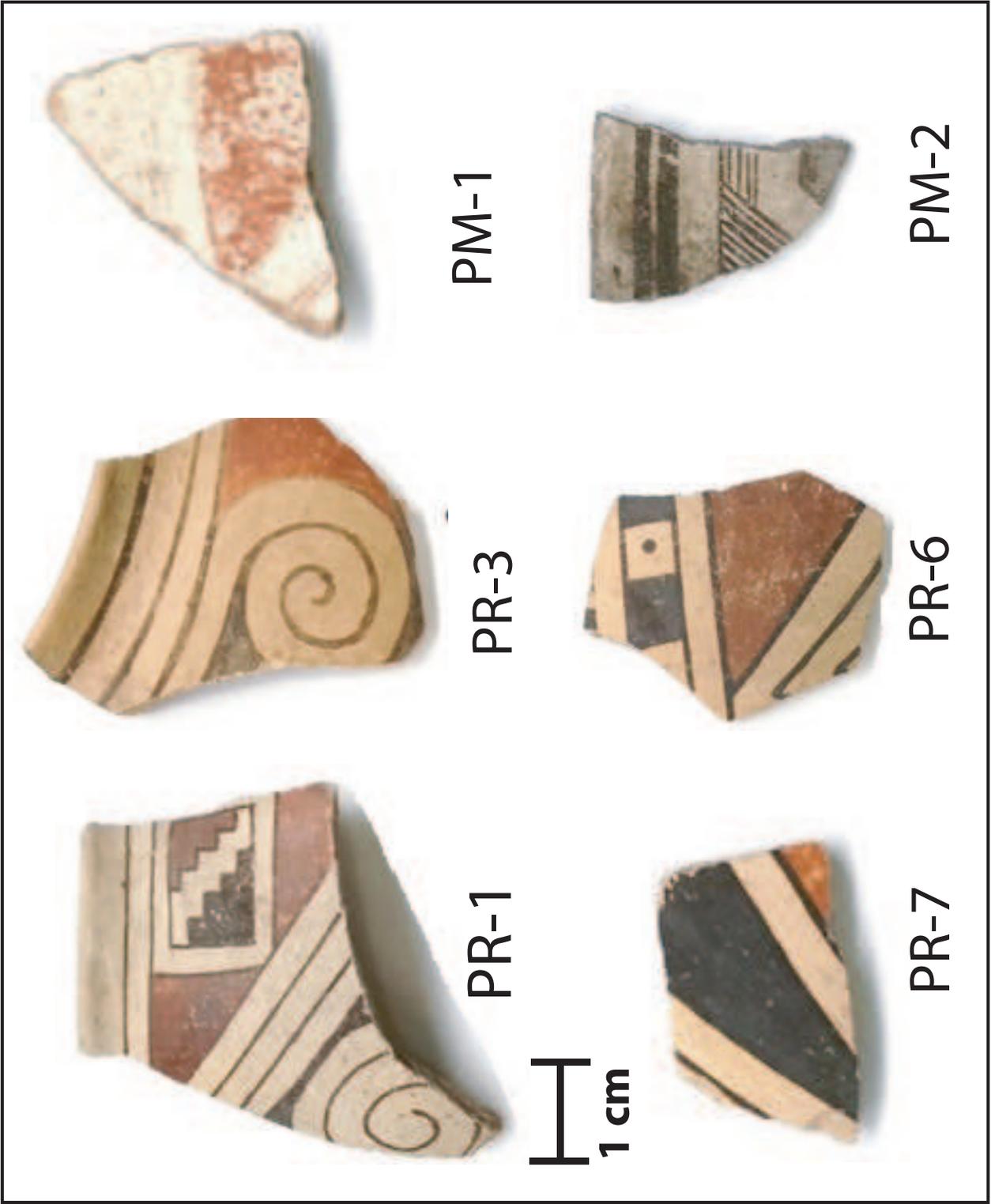
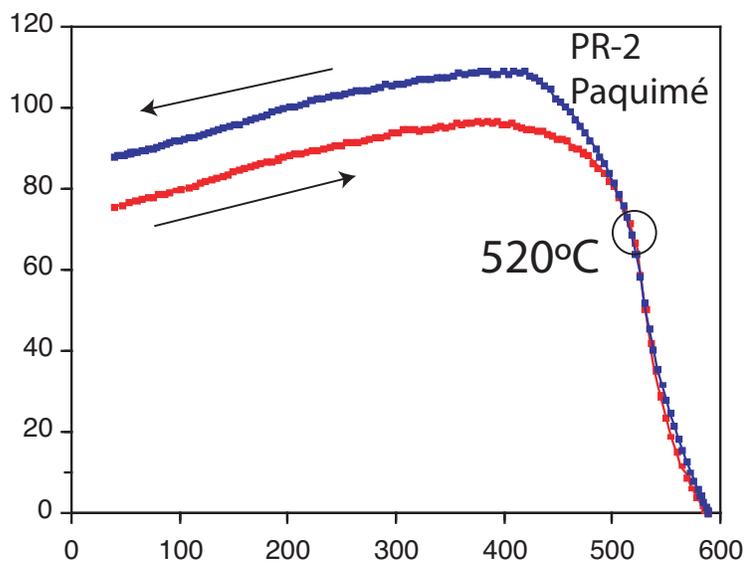


Figure 3

a) Ramos



b) Mimbres

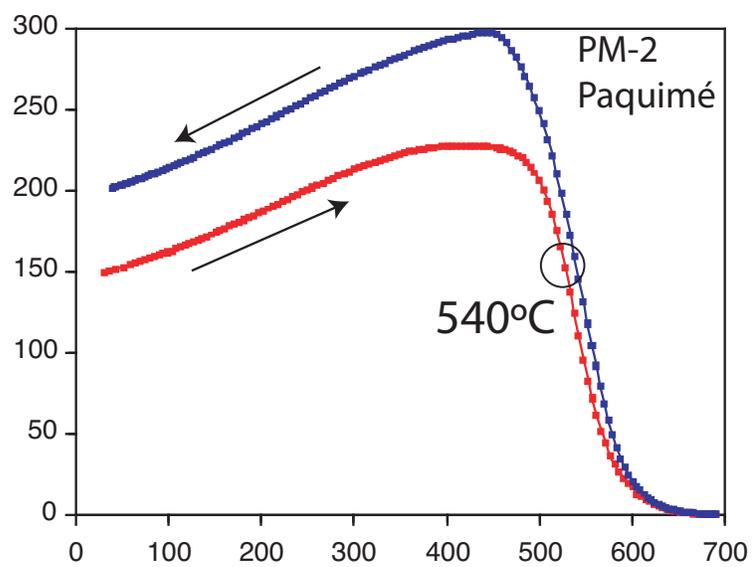
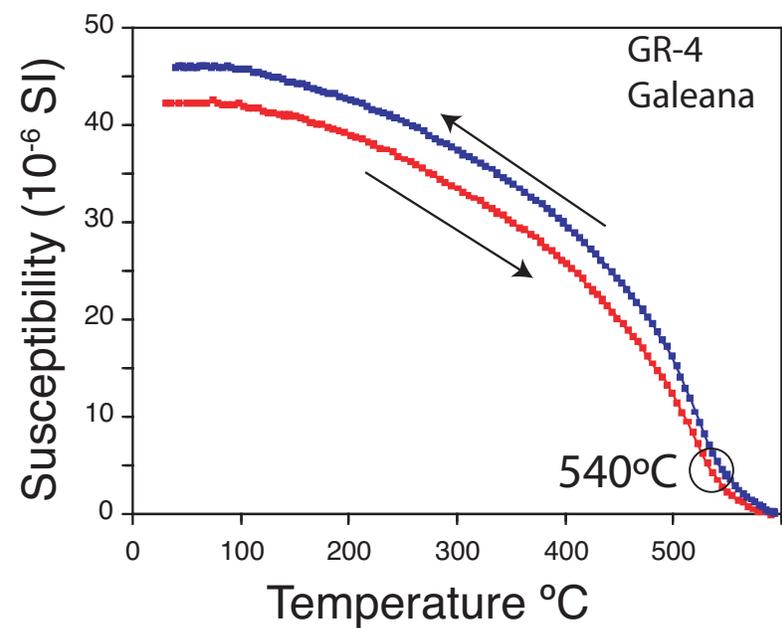
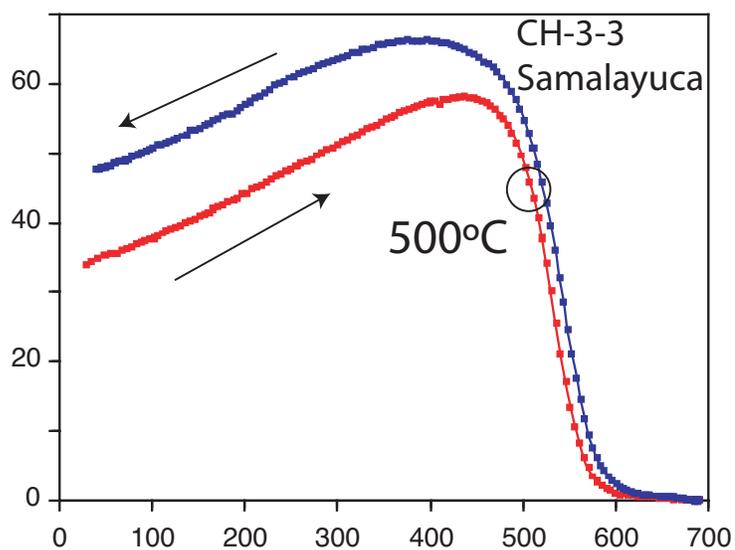
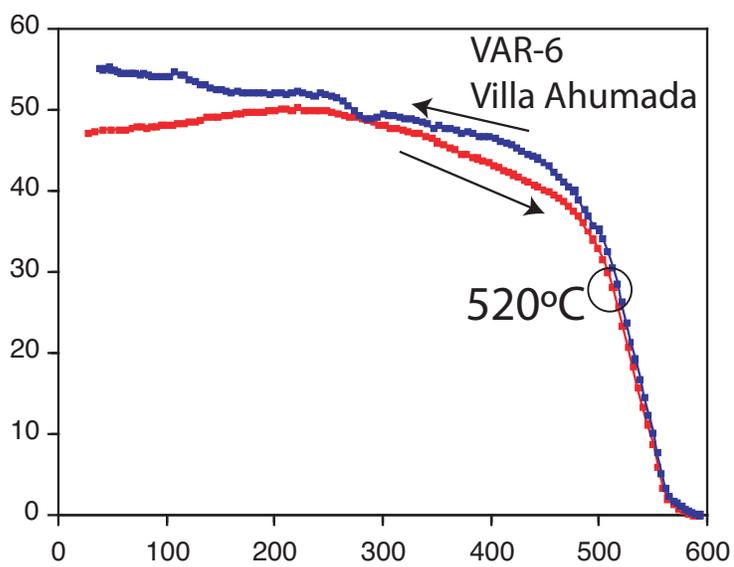
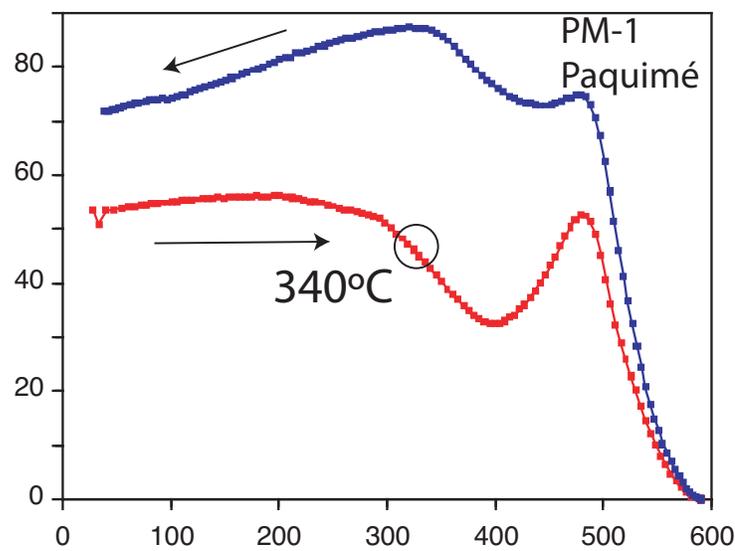


Figure 4

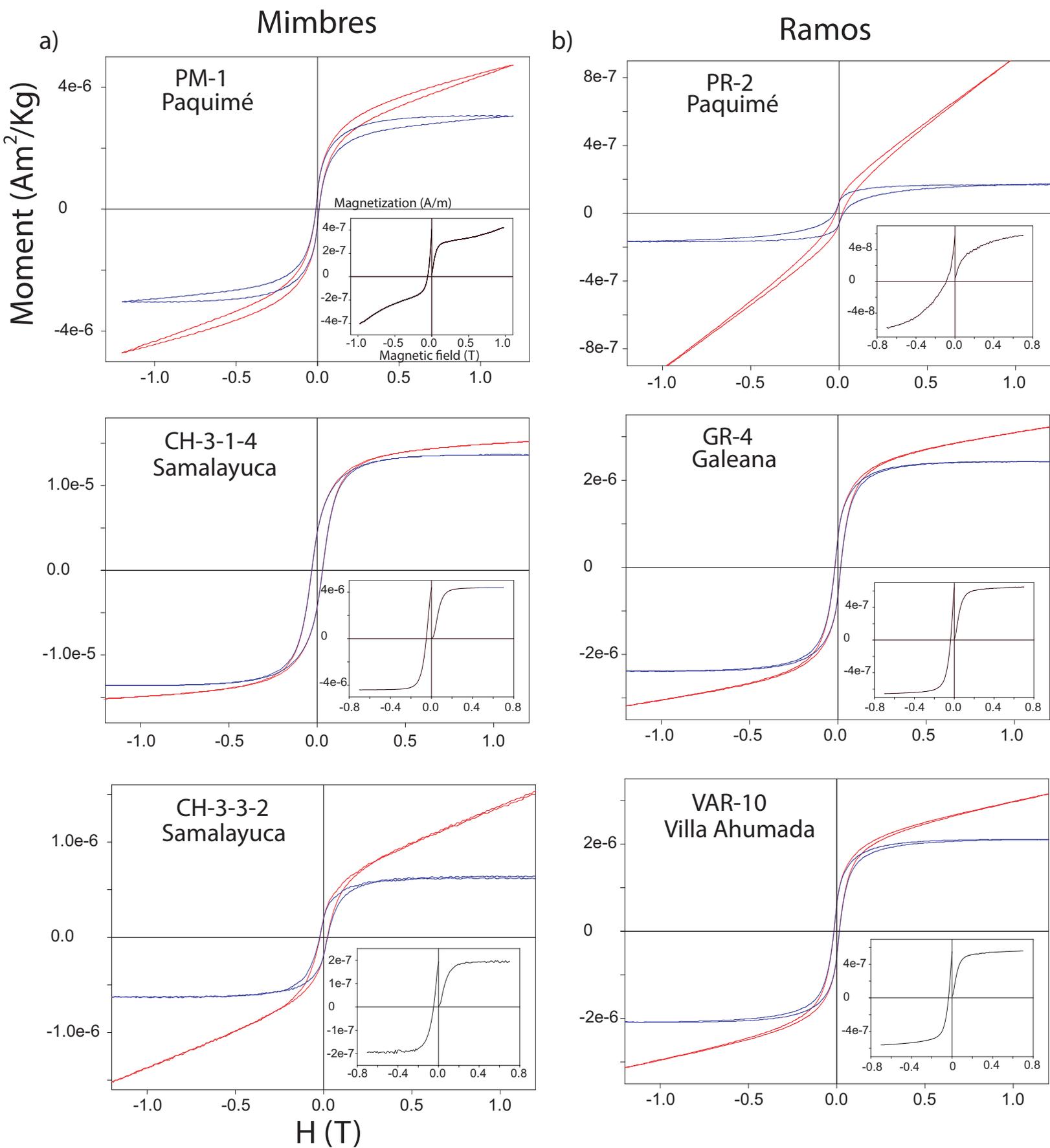


Figure 5

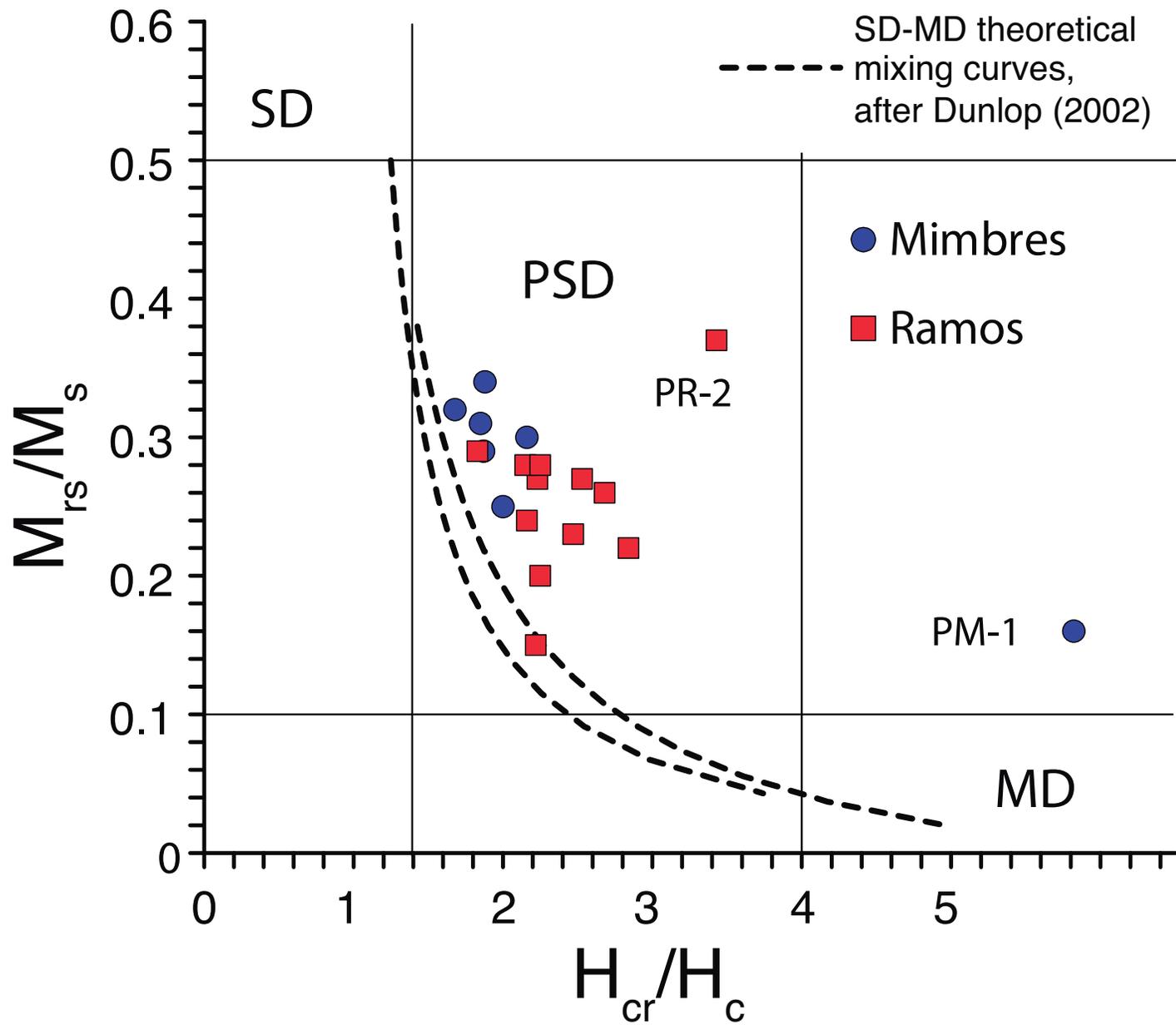


Figure 6

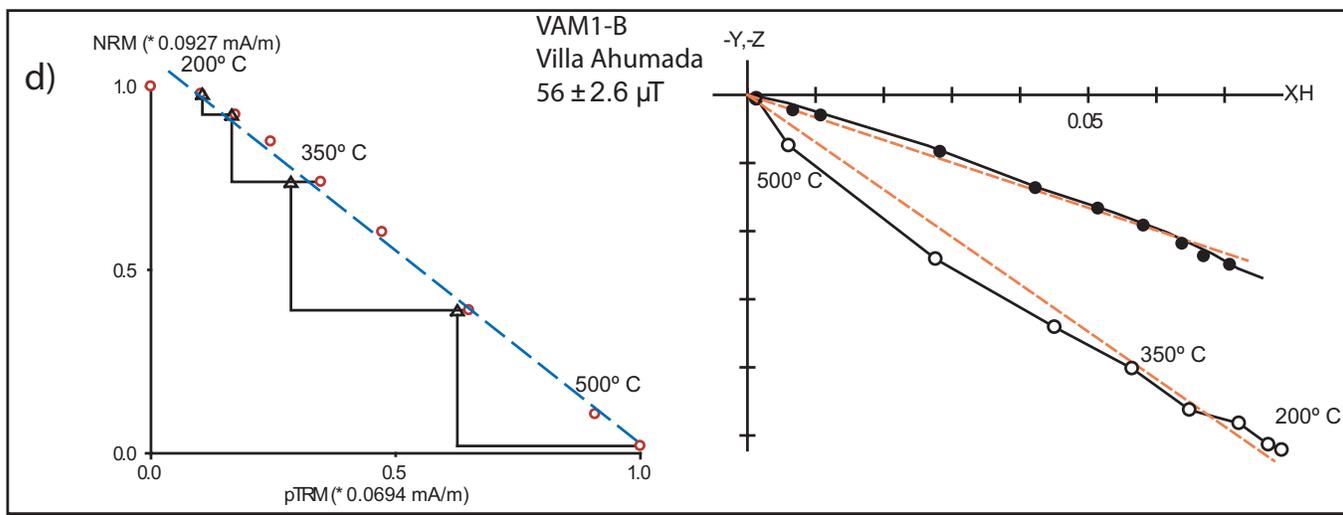
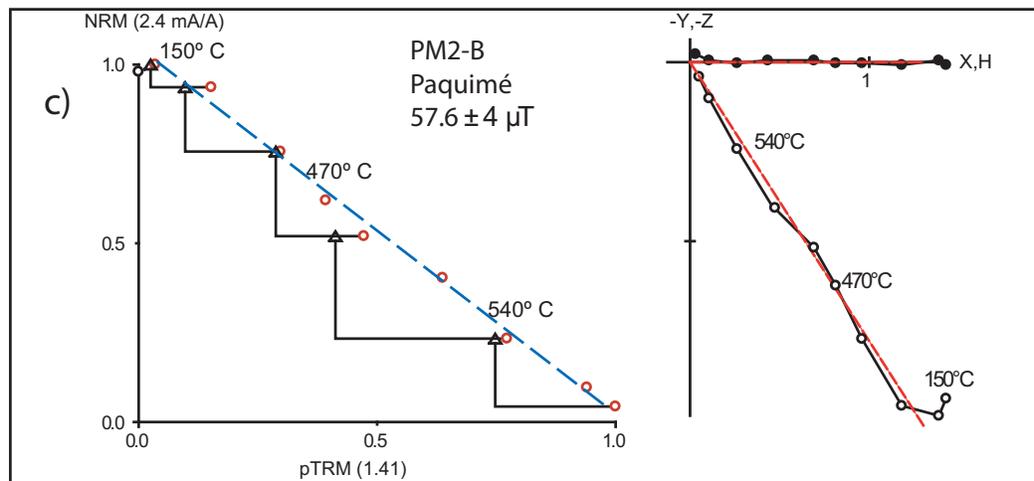
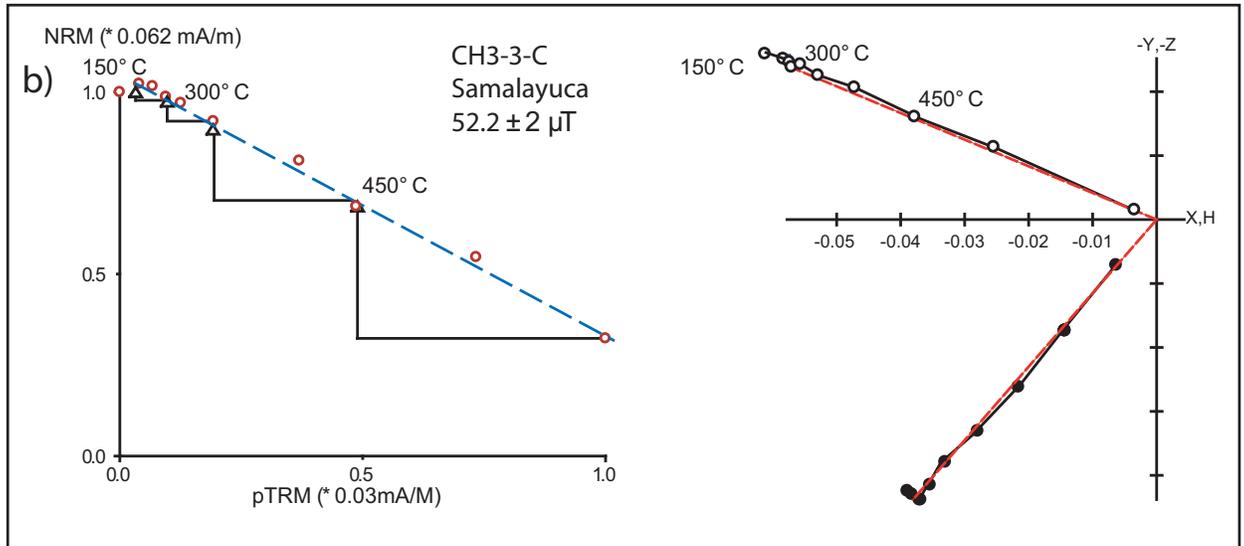
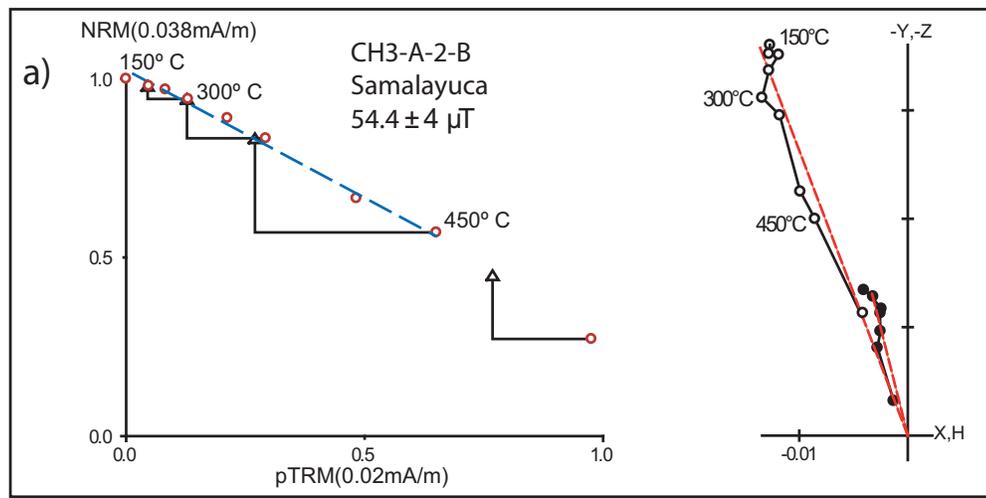


Figure 7

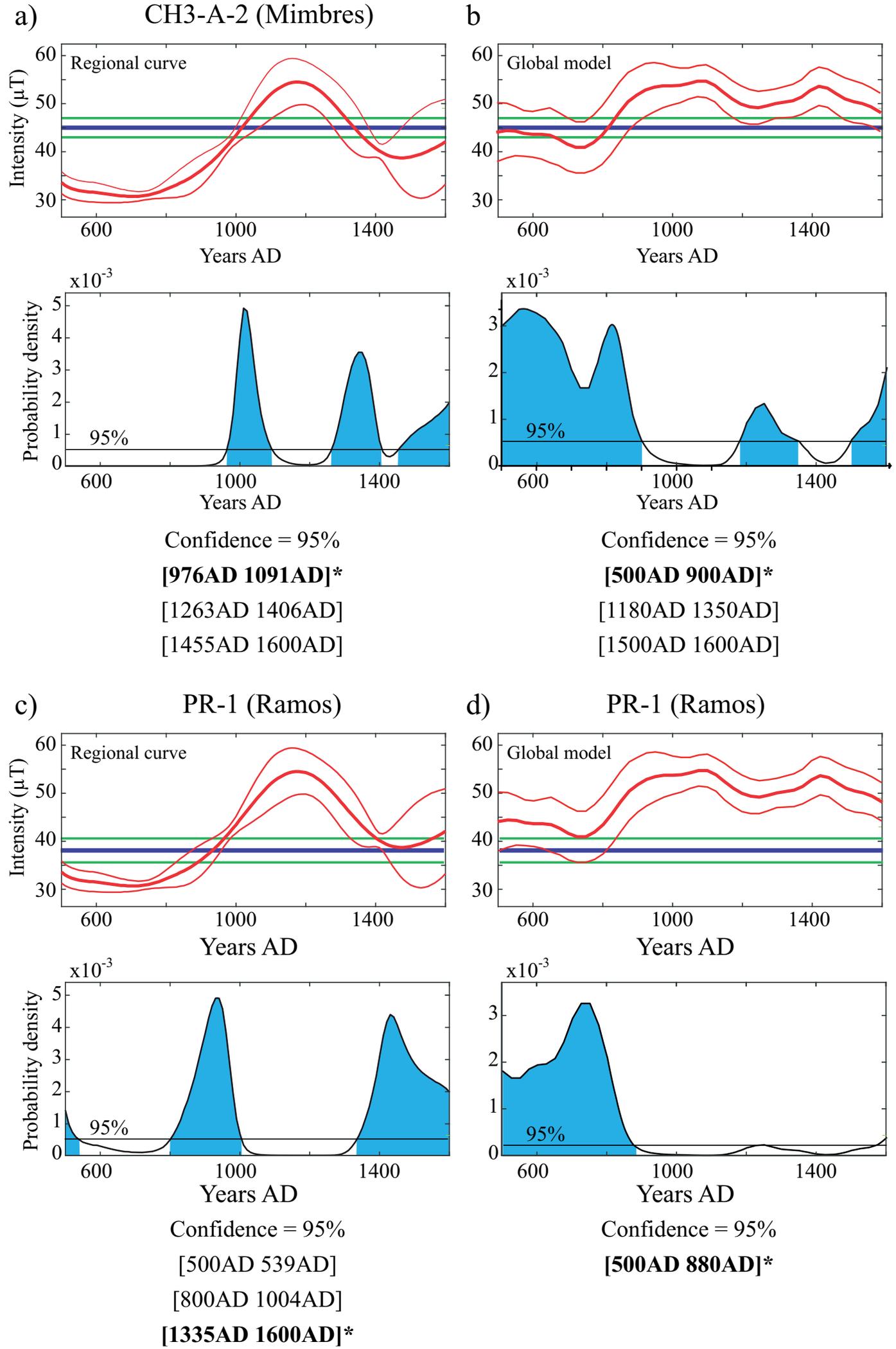


Figure 8

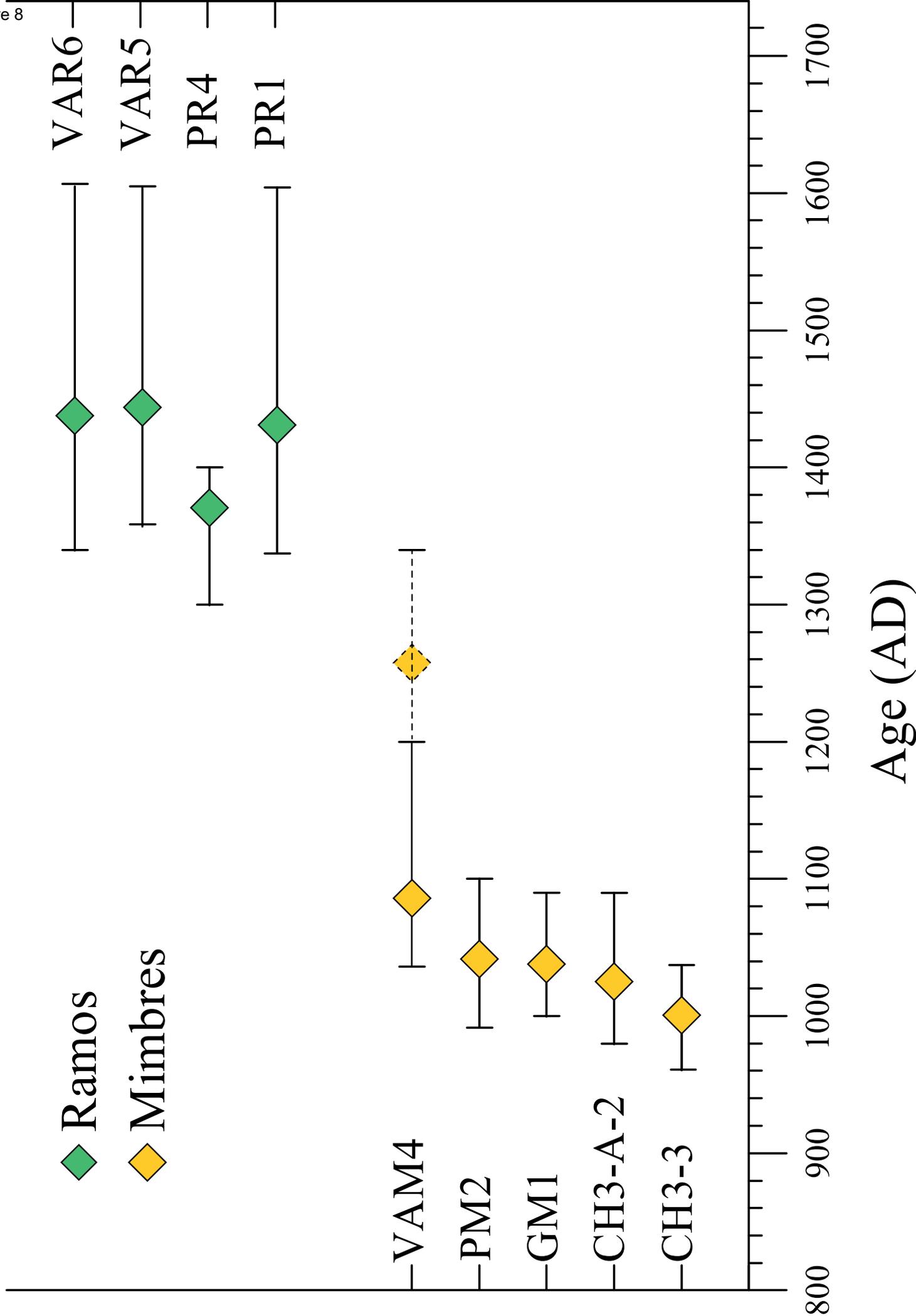


Table 1

<i>Archaeological site</i>	<i>Location</i>		<i>Sherd names</i>
	<i>Latitude °N</i>	<i>Longitude °W</i>	
Paquimé	30.3674	107.9485	PM & PR
Samalayuca	31.3424	106.4309	CH
Villa Ahumada	30.6165	106.5228	VAM & VAR
Galeana	30.1079	107.6116	GM & GR

Table 2

<i>Specimen</i>	<i>Ceramic Type</i>	<i>Mrs</i>	<i>Ms</i>	<i>Hc</i>	<i>Hcr</i>	<i>Mrs/Ms</i>
Allan-p	Mimbres	62.01	217.1	28.22	52.83	0.29
CH-3-1-4	Mimbres	220.3	686.8	30.45	51.15	0.32
Ch-3-3-1	Mimbres	23.27	67.5	31.79	59.71	0.34
Ch-3-3-2	Mimbres	5.942	19.63	22.75	49.21	0.30
PM-1	Mimbres	18.17	113.6	9.711	56.52	0.16
VAM-1	Mimbres	26.13	104.6	23.54	47.16	0.25
VAM-4	Mimbres	16.1	52.55	29.55	54.75	0.31
GR-1	Ramos	41.21	173.2	20.82	44.87	0.24
GR-4	Ramos	26.74	99.18	16.63	37.04	0.27
GR-6	Ramos	18.5	92.68	12.27	27.62	0.20
GR-7	Ramos	38.58	133.1	12.61	23.03	0.29
GR-8	Ramos	17.93	66.37	18.3	46.3	0.27
PR-1	Ramos	14.14	50.46	13.91	29.84	0.28
PR-2	Ramos	2.021	5.461	25.94	88.92	0.37
PR-3	Ramos	1.431	6.149	19.27	47.67	0.23
PR-7	Ramos	14.71	98.66	7.92	17.6	0.15
VAR-7	Ramos	5.356	20.36	14.77	39.54	0.26
VAR-8	Ramos	11.52	53	10.64	30.17	0.22
VAR-10	Ramos	19.26	69.18	15.58	35.1	0.28

Hcr/Hc

1.87

1.68

1.88

2.16

5.82

2.00

1.85

2.16

2.23

2.25

1.83

2.53

2.15

3.43

2.47

2.22

2.68

2.84

2.25

Table 3: Accepted archaeointensity results

Specimen	Locality	Type	N	Range °C	f	g	q	β	d(CK)	d(Pal)	α (°)	MAD _{anc} (°)	F _{raw±σ_F} (μ T)	F _{ATRM} (μ T)	F _{ATRM+CR} (μ T)	F _(ATRM+CR) (Mexico city) (μ T)	VADM _(ATRM+CR) ($\times 10^{22}$ Am ²)
CH3-3-A	Samalayuca	Mimbres	10	20-530	0.8	0.8	9.3	0.065	8.82	8.13	7.9	7.14	51.5±3.3	51.0	49.0		
CH3-3-B	Samalayuca	Mimbres	10	250-530	0.8	0.8	16.0	0.039	6.91	7.97	4.36	3.86	51.8±2.0	50.3	48.3		
CH3-3-C	Samalayuca	Mimbres	10	250-530	0.7	0.8	14.6	0.085	4.98	6.44	3.54	4.1	52.2±2.0	50.7	48.7		
CH3-3-D	Samalayuca	Mimbres	10	20-570	1.0	0.8	41.4	0.020	7.06	9.38	1.15	3.21	51.8±1.0	50.3	48.3		
Sherd-mean													51.8±0.3	50.6±.3	48.6±0.3	41.7±0.3	9.3
CH3-A-2-A	Samalayuca	Mimbres	10	20-530	0.7	0.8	7.4	0.070	2.74	5.71	9.67	3.82	56.3±3.9	55.6	53.4		
CH3-A-2-B	Samalayuca	Mimbres	8	20-450	0.4	0.8	5.8	0.073	2.77	5.99	4.45	1.83	54.4±4.0	54.4	52.2		
CH3-A-2-C	Samalayuca	Mimbres	9	300-520	0.8	0.8	4.9	0.136	6.62	5.76	3.44	4.9	56.1±9.9	56.1	53.9		
CH3-A-2-D	Samalayuca	Mimbres	10	20-530	0.8	0.8	9.2	0.087	6.62	5.76	3.44	4.9	50.1±3.3	50.1	48.1		
Sherd-mean													54.2±2.9	54.1±2.7	51.9±2.6	44.5±2.2	10.0
GM1-A	Galeana	Mimbres	7	330-480	0.4	0.8	4.7	0.093	8.82	10.12	7.9	6.14	55.7±3.9	54.6	52.4		
GM1-B	Galeana	Mimbres	9	20-540	0.9	0.8	5.1	0.076	7.53	8.44	3.6	4.54	56.1±4.1	55.7	53.5		
GM1-C	Galeana	Mimbres	8	20-540	0.8	0.7	5.6	0.010	4.67	6.71	2.9	3.04	55±5.4	53.2	51.1		
GM1-D	Galeana	Mimbres	9	300-520	0.6	0.8	5.6	0.069	8.49	0.73	2.69	2.44	58.9±6.7	55.9	53.7		
Sherd-mean													56.4±1.7	54.9±1.2	52.7±1.2	45.9±1.0	10.3
PM2-A	Paquimé	Mimbres	11	150-570	1.0	0.9	7.0	0.086	7.12	8.41	1.43	3.17	56.7±7.0	57.9	55.6		
PM2-B	Paquimé	Mimbres	6	150-520	0.6	0.8	7.1	0.075	7.56	9.27	4.31	2.45	57.6±3.6	55.4	53.2		
PM2-C	Paquimé	Mimbres	6	20-495	0.8	0.8	31.0	0.059	5.97	7.56	2.43	2.82	51.6±1.0	53.2	51.1		
PM2-D	Paquimé	Mimbres	10	20-570	1.0	0.9	16.0	0.053	6.98	9.45	0.91	2.66	56.5±3.0	55.4	53.2		
Sherd-mean													55.6±2.7	55.5±1.9	53.3±1.8	46.2±1.6	10.4
VAM4-A	Villa Ahumada	Mimbres	8	20-450	0.4	0.7	3.3	0.089	3.28	4.96	5.14	3.01	63.4±5.5	61.5	59.0		
VAM4-B	Villa Ahumada	Mimbres	8	20-450	0.4	0.7	3.3	0.075	1.45	5.09	5.95	2.41	61.7±3.4	61.1	58.7		
VAM4-C	Villa Ahumada	Mimbres	7	20-450	0.4	0.8	5.5	0.085	2.17	4.68	6.6	1.98	60±4.1	59.7	57.3		
VAM4-D	Villa Ahumada	Mimbres	7	330-450	0.8	0.6	5.2	0.044	9.4	7.38	0.86	1.26	66.9±6.2	63.4	60.9		
Sherd-mean													63.0±2.9	61.4±1.5	59.0±1.5	51.0±1.3	11.4
GR1-B	Galena	Ramos	8	20-450	0.3	0.8	5.5	0.043	1.55	5.16	0.27	1.72	44.7±2.0	45.2	43.4		
Sherd-mean													<i>na</i>	<i>na</i>	<i>na</i>	<i>na</i>	<i>na</i>
PR1-A	Paquimé	Ramos	5	20-270	0.4	0.6	5.2	0.055	7.43	9.34	5.85	4.61	37.3±3.6	36.2	34.8		
PR1-B	Paquimé	Ramos	10	20-430	0.7	0.7	4.8	0.075	8.12	7.62	6.49	7.06	41.2±4.4	40.4	38.8		
PR1-C	Paquimé	Ramos	5	20-270	0.4	0.6	3.9	0.083	3.27	1.38	11.7	5.07	49.3±4.6	48.1	46.2		
PR1-D	Paquimé	Ramos	9	290-570	0.6	0.8	8.5	0.055	5.61	2.78	9.01	7.79	48.8±2.6	47.9	46.0		
Sherd-mean													44.2±5.9	43.2±5.9	41.1±5.6	36.0±4.9	6.9
PR4-A	Paquimé	Ramos	6	150-450	0.6	0.7	4.9	0.051	5.88	8.39	4.38	2.85	57.4±1.4	53.1	51.0		
PR4-C	Paquimé	Ramos	7	150-450	0.7	0.6	20.8	0.045	1.18	2.23	3.94	1.95	49.8±1.1	47.0	45.1		
PR4-D	Paquimé	Ramos	5	150-450	0.5	0.7	6.2	0.063	2.48	4.67	5.23	2.06	54.5±2.7	53.5	51.4		
PR4-E	Paquimé	Ramos	7	20-450	0.7	0.6	20.8	0.022	1.18	2.23	3.94	1.95	51.6±1.1	49.8	47.8		
Sherd-mean													53.3±3.3	50.9±3.1	48.8±2.9	42.4±2.5	9.5

VAR5-A	Villa Ahumada	Ramos	7	330-520	0.6	0.6	4.8	0.054	4.81	7.34	6.17	4.69	45.7±3.3	43.9	42.1		
VAR5-B	Villa Ahumada	Ramos	8	330-520	0.6	0.6	5.4	0.069	5.17	6.18	14.4	6.05	46.3±2.9	42.1	40.4		
VAR5-C	Villa Ahumada	Ramos	9	330-520	1.0	0.8	16.4	0.091	6.89	9.79	2.5	5.04	49.8±2.2	48.4	46.5		
VAR5-D	Villa Ahumada	Ramos	7	300-520	0.8	0.7	12.5	0.047	5.17	6.19	14.4	6.07	42.9±3.1	42.1	40.4		
Sherd-mean													46.2±2.8	44.1±3.0	42.4±2.9	36.6±2.5	8.2
VAR6-A	Villa Ahumada	Ramos	7	300-540	0.7	0.7	8.2	0.059	6.13	8.45	6.29	2.33	44.3±2.8	43.4	41.7		
VAR6-B	Villa Ahumada	Ramos	6	300-540	0.6	0.7	6.3	0.067	4.54	7.13	2.05	3.6	44.1±2.9	42.8	41.1		
VAR6-C	Villa Ahumada	Ramos	9	20-540	1.0	0.8	16.4	0.046	5.02	6.97	3.1	3.4	49.8±2.2	48.4	46.5		
Sherd-mean													46.1±3.2	44.9±3.1	43.1±3.0	37.3±2.5	8.4

Table 4

Sherd	Type	Age range (years AD)	
		Mahgoub local curve	SHAWQ2k global model
CH3-3	Mimbres	960-1020	500-820
CH3-A-2	Mimbres	980-1090	500-900
GM1	Mimbres	1000-1090	500-910
PM2	Mimbres	990-1100	500-920
VAM4	Mimbres	1040-1100	840-1600
	Mimbres	960-1100	500-1600
PR1	Ramos	1340-1600	500-880
PR4	Ramos	1300-1410	500-890
VAR5	Ramos	1360-1600	500-820
VAR6	Ramos	1340-1600	500-810
	Ramos	1300-1600	500-890