

1 **Natural clays used in pharmaceuticals and cosmetics: mineralogical**
2 **characterization and relationships with major- and trace-elements compositions**

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7 **Key words:** clays, clay minerals, cosmetics, pharmaceuticals, trace elements

8
9 **Abstract**

10 The present study was carried out to determine the suitability of fifteen natural clay samples (green,
11 white and brown) purchased in local stores and used for pharmaceutical and cosmetic use. The
12 mineralogical composition of both the bulk sample and the clay fraction was determined from X-ray
13 powder diffraction, and the clay mineralogy was compared with the relative bulk chemical
14 composition (major- and trace-elements), mainly focusing on the trace elements that are prohibited
15 in cosmetics concentrations.

16 The bulk mineralogical composition of the studied clay samples is characterized by the presence of
17 a significant non-clay fraction made up of calcite, quartz, and minor dolomite, feldspars and
18 gypsum. The clay fraction is composed by illite, smectites, kaolinite and chlorites in variables
19 amounts and diverse associations. The more represented samples are green clays being composed of
20 smectites + illite + chlorites, with considerable amounts of Ni and Sr, while other green samples are
21 only composed by illite and are enriched in Rb and As. The pure smectite samples (both brown and
22 white in color) are depleted in almost all the trace elements and, therefore, they represent the more
23 suitable sample to be commercialized. On the contrary, the white kaolinite-rich sample is notably
24 enriched in Zn, As, Ba, La, Pb and Th, and thus it is the most hazardous product for human health.

25
26 **Introduction**

27 Clays are fine-grained (normally $< 2 \mu\text{m}$) natural rock or soil materials that combines one or more
28 clay minerals with lesser quantities of other minerals and/or organic products such as quartz,
29 feldspars, carbonates, sulphates, Fe and/or Al oxides, humus, etc. (Guggenheim and Martin, 1995).
30 In the field of health, clay minerals and clays are extensively used in pharmaceutical (treatment) or
31 cosmetic (care and beauty) purposes because of their high specific surface area, optimum
32 rheological characteristics and excellent ion exchange capability (Patel et al., 1986; Summa et al.,
33 1998; Carretero, 2002; Tateo et al., 2006; Choy et al., 2007; Lòpez-Galindo et al., 2007; Viseras et
34 al., 2007).

35 The use of a clay for any specific application depends on (i) the mineralogical composition, i.e. the
36 type of clay mineral, (ii) the structure of the clay mineral (1:1 or 2:1 layer type) and (iii) its
37 chemical composition. The different types of cations in the octahedral sheet, as well as isomorphic
38 substitutions in the octahedral and tetrahedral sheets, can generate different mineral phases giving
39 rise to varied technical behaviour (e.g. Grim, 1968; Velde, 1995). For example, because of their
40 structural and chemical characteristics, both kaolinite and talc show minimal layer charges,
41 presenting low cation-exchange capacities. In contrast, smectites are characterised by octahedral
42 and tetrahedral substitutions and high ion-exchange capacities (Bergaya et al., 2006). Moreover,
43 textural differences between structurally and chemically identical clay minerals also affect their
44 adsorptive and rheological properties (Lagaly, 1989; Murray and Keller, 1993; Viseras, 1997;
45 Yebra, 2000).

46 In order to be suitable in pharmaceutical or cosmetic applications, clays must comply with a number
47 of chemical (stability, purity, chemical inertia), physical (texture, water content, particle size) and
48 toxicological (atotoxicity, safety and microbiological purity) requirements (Lòpez-Galindo and
49 Viseras, 2004; Lòpez-Galindo et al., 2007; Tateo and Summa, 2007; Viseras et al., 2007).
50 Specifically, they must have zero or very low toxicity, as regulated in the European Community by
51 the EC Regulation 1223/2009, a simplification of the Community Directives 76/768/EEC and
52 2001/58/EC. In addition, the Occupational Safety and Health Administration (US Department of

53 Labor, OSHA CFR 1910.1200) establishes the safety information that must accompany different
54 commercialized products. In the case of clays, such information must include an accurate
55 identification of the substance (i.e. mineralogical and chemical compositions), information on
56 ingredients, hazards identification, handling and storage, physical and chemical properties, stability
57 and reactivity and toxicological information. It should be note that the high adsorption capacity of
58 clays can lead to the accumulation of trace elements, some of which may be considered as
59 potentially toxic (Mascolo et al., 1999; Gomes, 2003; Gomes and Silva, 2007; Lòpez-Galindo et al.,
60 2007; Carretero and Pozo, 2009; Silva et al., 2011).

61 Notwithstanding this, and despite several articles are available in the literature on the use of clay
62 minerals in health sciences, very few information are available about the mineralogical and
63 chemical composition of clays used in pharmaceutical and cosmetic purposes. Indeed, these
64 products are often characterized (and commercialized) only based on their color (e.g. white, green,
65 brown, pink, yellow), which reflect differences in mineralogical and organic content. In this work a
66 selection of natural clays, commercially available in the market as white, green and brown clays,
67 have been studied with the aim to determine their mineralogical composition in terms of both the
68 bulk sample and the clay fraction. Furthermore, their bulk chemical compositions (major- and trace-
69 elements) have been used to investigate whether there is any correlation between clay mineralogy
70 and chemistry, mainly focusing on the trace elements that are prohibited in cosmetics
71 concentrations (EC Regulation 1223/2009).

72

73 **Materials and methods**

74 Analysis were carried out in fifteen natural clay samples purchased in local stores of the Italian
75 market. Most of the clays were contained in 0.5 kg sacs. About 0.5 kg of sample was weighed
76 individually, dried in an oven at 30°C for 24 hours and the dried samples were weighed and
77 homogenized.

78 Primary investigations included mineralogical analyses of the bulk sample and the clay fraction (<2
79 mm) by X-ray powder diffraction (XRPD). Secondary, the acquired mineralogical data have been
80 compared with the chemical (major- and trace-element) composition of the bulk samples, which
81 have been extensively reported in a companion paper (Roselli et al., 2015).

82 Mineralogical analyses were carried out using a Philips X'Change PW 1830 diffractometer (Cu Ka
83 radiation). Randomly oriented powders were prepared by gently hand crushing bulk samples and
84 side loaded into an aluminium holder for analysis of unoriented powder (bulk composition). They
85 were analysed a 0.02° step, with a counting time of 1 s/step from 2° to 60° 2 θ . The analytical
86 conditions were a 35 kV accelerating potential, a 30 mA filament current. All major peaks were
87 indexed in the refinement, and quartz served as an internal standard. Successively, the <2 μ m clay
88 fraction was extracted by crushing, dispersion, and two-stage centrifuge, according to Moore and
89 Reynolds (1997). Oriented clay mounts were prepared and analysed under conditions of air dried,
90 ethylene glycolated, and heated to 335°C, then to 550°C for two hours. These were analysed a 0.02°
91 step, with a counting time of 1 s/step from 2° to 30° 2 θ , and examined in composite diffractograms.
92 According to the procedures proposed by various authors (e.g. Brown and Brindley, 1980; Velde,
93 1995; Moore and Reynolds, 1997; Setti et al., 2004), the mineral identification followed standard
94 methods and was based on the shape, position and intensity of specific reflections. Kaolinite and
95 chlorite were distinguished by the slow scan method of Biscaye (1964) over the 004 peak of chlorite
96 and the 002 peak of kaolinite. Where these peaks were too small to allow an accurate position, the
97 002 peak of chlorite and the 001 peak of kaolinite were used. This assumes that a peak position of
98 7.10 Å indicates chlorite and 7.16Å indicates kaolinite (Biscaye, 1964). Illite and mixed-layer clays
99 were identified from diffractograms of samples treated with ethylene glycol by referring to
100 Reynolds (1980), Moore and Reynolds (1997) and Srodon (1980). The 7Å reflection in dry
101 samples, which was completely lost after heating to 550°C, was attributed to kaolinite. The 10Å
102 reflection which was not affected by chemical treatment or heating indicated the presence of illite.
103 The occurrence of smectites was evidenced by the reflection at d=18.3-18.9Å after EG solvation.

104 For the semi-quantitative analyses of the bulk sample composition, the relative abundances of
105 minerals were estimated from the heights of the main reflections. The following peaks and
106 corrections factors (CF) were used for the estimation: quartz (4.26 Å),CF 1; calcite (3.03 Å),CF 0.4;
107 alkali feldspar (3.24 Å),CF 0.9; plagioclase (3.18 Å),CF 0.5; mica (10 Å),CF 2.8; chlorite (7 Å),CF
108 2.8; smectite (15 Å on glycolated sample), CF 6.5.Semi-quantitative analysis of the clay fraction
109 was performed by measuring the integrated peak areas of the main basal reflections on glycolated
110 samples: smectite at 17Å, illite at 10 Å and kaolinite/chlorite at 7 Å. The values of peak areas were
111 converted into relative concentrations using the weighting factors of Biscaye (1964) and the degree
112 of crystallinity was evaluated according to the methods of Biscaye (1965) and Thorez (1976). This
113 method was tested by the use of kaolinite and pyrophyllite internal standard and the results well
114 agree (confidence level for correlation coefficient = 0.9). The overall error for any particular clay
115 for this method is unknown, but repeated tests indicate it is internally consistent. However, as
116 indicated by Moore and Reynolds (1997), the error for xrd-derived results can be estimated at
117 around 10%.

118

119 **Results and discussion**

120 *Mineralogical composition of the bulk sample*

121 The results of bulk mineralogical analyses of the studied samples, as well as their color and pH, are
122 reported in Table 1, whereas their X-ray patterns are presented in Fig. 1.

123 Concerning bulk composition, all samples are characterized by the presence of a significant non-
124 clay fraction (from ~11 to ~64%) and it is represented by calcite, dolomite, quartz, feldspars and
125 gypsum. Silicate and carbonate minerals such as quartz, feldspars, calcite and dolomite are very
126 common phases and have been found in almost all samples.

127 In the bulk samples, calcite and dolomite are found as carbonate minerals. Calcite is generally the
128 most abundant non-clay phase (~13-24%, excluding three samples) and it is identified by weak
129 reflections at 3.03 Å. Dolomite is present in ~73% of the total samples but its content is generally

130 low (~4-12%); it is identified by distinctive reflection at 2.88 Å. No secondary peak for dolomite
131 appears in the XRD indicating trace amount of this mineral. Quartz is always present as a common
132 constituent of clays (~3-13%) and in two samples it is comparable (~23%, AR12) or higher (~33%,
133 AR15) with respect the calcite content. Quartz is identified by distinctive reflections at 4.26 Å, 3.34
134 Å, 2.46 Å, 2.28 Å, 2.24 Å, 2.13 Å, 1.98 Å, 1.81 Å, 1.67 Å, 1.54 Å and 1.45 Å. It gives a strong
135 diffraction pattern with sharp reflections (Fig. 1). The strongest reflection is observed at 3.34 Å
136 (101), which is several times more intense than the (100) peak at 4.26 Å. Feldspar forms a minor
137 component of clays and its content is generally very low(~2-9%). The studied samples contain both
138 alkali feldspars (orthoclase and microcline) and plagioclase feldspars. Alkali feldspars are identified
139 by their main reflections of 3.79 Å (orthoclase) and microcline (3.24 Å) whereas for plagioclase, the
140 presence of distinct and prominent peak at 3.20 Å is considered. Gypsum is very rare and it has been
141 detected in only two samples in low (~3%, AR1) or significant (~35%, AR2) amount. One sample
142 (AR9) also contain cristobalite (~6%).

143

144 *Mineralogical composition of the clay fraction*

145 After the semi-quantitative identification of mineral phases in the studied bulk samples, the next
146 step was to obtain a semi-quantitative result regarding the mineral species in the clay fraction.
147 These results are presented in Table 2, whereas the X-ray patterns of the air dried, ethylene
148 glycolated and heated samples are illustrated in Fig. 2.

149 The clay fraction (<2µm) of the studied samples exhibit strong first-order reflections, often with
150 asymmetrical shapes and a few associations of weak and broad diffraction bands or shoulders. The
151 behaviour of minerals reflections under natural conditions (air-dried, ethylene glycolation and
152 heating to 335°C and 550°C), define a very diverse set of clay minerals represented by illite,
153 smectites, kaolinite and chlorites. Based on type (and association) of clay minerals, the studied
154 samples can be divided into five groups.

155 The group 1 is the most represented (53% of the total samples) and has a clay fraction formed by
156 prevailing illite+chlorites, with subordinate smectites. The group 2 (20% of the total samples) is
157 entirely composed by illite, whereas the group 3 (16% of the total samples) is made up of smectites.
158 Groups 4 and 5 correspond to isolated samples that have a clay fraction composed of kaolinite +
159 illite+ smectites (AR3) and illite + chlorites (AR9), respectively.

160 Illite is characterized by a 10 Å ($\sim 8.9^\circ 2\theta$) basal reflection (001) and its (002) reflections at 4.98 Å-
161 5.03 Å ($\sim 17.7^\circ 2\theta$, Fig. 2). It is also identified at 3.33 Å to 3.35 Å ($\sim 26.8^\circ 2\theta$), even if this
162 reflection is often hidden by the 3.34 Å peak of quartz, probably also present in very small amounts
163 in the separated clay fraction. The position of these reflections is not modified after swelling using
164 organic solvents (ethylene glycol), nor by heat treatment at 335 and 550°C. In some samples, on
165 heating to 550°C the (001) peak of illite may show slight collapse, suggesting that expandable
166 layers could also be present. In most of samples, the sharp peaks of illite indicate that illites are
167 generally well crystallized. Illite is present in almost all the investigated samples (except group 3)
168 ranging from $\sim 28\%$ to $\sim 66\%$ with an average of $\sim 38\%$ among the clay minerals. In particular, it is
169 the only clay mineral in the group 2.

170 Smectites are easily identified by comparing diffraction patterns of air-dried and ethylene
171 glycolated preparations. The air-dried sample gives a very strong 001 reflection at about $6^\circ 2\theta$
172 ($\sim 15\text{Å}$) which shifts at about 5.2° ($\sim 17\text{Å}$) in the glycol-treated condition, and collapses to 10 Å after
173 550°C heat treatment.

174 Kaolinite is only present in one sample (AR9), where it represents the main clay mineral ($\sim 51\%$). It
175 is identified from well defined, characteristic 7 Å and 3.57 Å peaks (Fig. 2). Kaolinite is found to be
176 unaffected on glycolation and 335°C heat treatment. On heating to 550°C, kaolinite tends to lose its
177 crystalline character whereas chlorite at this temperature is partially dehydrated, causing increased
178 intensity at the 14 Å reflection (Grim 1968) and this confirm the identification of the kaolinite and
179 chlorite.

180 Chlorites are present in the groups 1 and 4, as indicated by the presence of a strong 001 reflection at
181 14 Å reflection that retains its location and magnitude through glycolation and heating,
182 accompanied by the (002) reflection at ~ 7.07 Å and that disappear after 550°C heat treatment, as
183 well as happened to the 4.7 Å and 3.5 Å reflections.

184 Analysis from XRPD indicate that all samples are not pure clays being characterized by the
185 presence of a significant non-clay fraction dominated by calcite and quartz, and to a minor extent by
186 dolomite, feldspars and gypsum. Different to what reported in literature, which stated that clay
187 minerals used in pharmaceuticals and cosmetics are only smectites, palygorskite, kaolinite and talc,
188 the studied sample have a clay fraction composed by a very diverse set of clay minerals represented
189 by illite, smectites, kaolinite and chlorites. Moreover, we would here also point out that there is a
190 great uncertainty regarding the use of color as “compositional term” for clays. The group 1 samples,
191 constituted by smectites+illite+chlorites, are available in the market as “green clays”, as well as the
192 group 2 samples, which are only made up by illite. AR1 is a “brown clay” whereas AR7 is a “white
193 clay”, but they have the same clay mineral (smectite). Moreover, AR9 is also a “white clay”, but it
194 includes kaolinite+illite+smectite.

195 196 *Relationships between mineralogical composition and bulk chemistry*

197 The healing use of clay is widespread, but often the mineralogical and chemical compositions of the
198 raw materials are scarcely known. This is rather surprising if we consider that natural materials are
199 highly variables and could be very rich in dangerous or toxic minerals and/or trace chemical
200 elements. Using major- and trace-element data reported in a companion paper (see Roselli et al.,
201 2015 for methods and whole dataset), we try to compare the mineral composition of the studied
202 samples with their bulk chemistry, in order to assess whether the presence of a specific clay mineral
203 can be linked to the presence of a particular chemical element. In Figs. 3 and 4 major- and trace
204 elements data of the investigated clays have been related to their silica content, and the samples
205 were grouped according to their mineralogical composition. These compositions were also

206 compared to average crustal clays worldwide (Pettijohn, 1957; Turekan and Wedephol, 1961;
207 Mason and Moore, 1982; Gromet et al., 1984).

208 The eight samples of group 1 show a very homogeneous chemical composition, according to their
209 similar mineralogy (smectites + illite + chlorites). They show the highest Ca contents, probably also
210 due to the significant presence of calcite (~14-16%) in the bulk composition, whereas they are
211 intermediate to low as regards the other major elements. In terms of trace elements, they are notably
212 high in Ni, Cu, Sr, and show low As contents. On the contrary, the samples containing illite (group
213 2) show comparable contents for major- and some trace elements (e.g. Al, Ca, Mn, Ti, Fe, K, Ni, Ba,
214 Cu, Sr, Th) while they are clearly distinct for other trace elements such as Zn, Rb, Pb, As and La.
215 They show high contents of Al, K, Ti, Zn, As and Rb (especially the illite-richest AR4 sample) and
216 low amounts of Ca, Mn and Sr. A similar behavior is shown by the two smectite-bearing samples of
217 group 3, which exhibit very similar Ca, Mn, K, Ni, Rb and Pb contents and significantly different
218 Al, Ti, Fe, Zn, Ba, Cu, La and Th amounts. One of these samples (AR1) shows the lowest contents
219 of almost all the major (excluding Ca) and the trace (excluding Cu and Sr) elements, whereas the
220 other sample (the smectite-richest AR7) is generally coherent with the illite-bearing samples. As
221 regard the two isolated samples, AR3 has a chemical composition comparable with that of the group
222 1 samples except for Ca, Mn, Ni and As, whereas AR9 has a bulk chemistry very different from that
223 of all other studied samples. It is characterized by the highest contents of Al, Zn, As, Ba, La, Pb and
224 Th, and the lowest amounts of Ni, Cu, Sr, Fe and Ca. The lowest Ca content may also be related to
225 the absence of calcite in the bulk composition. S content (not shown in Figs. 3 and 4) is very high in
226 sample AR1 (group 1) and this is probably due to the abundant presence of gypsum (~35%). For
227 particular trace elements such as Ni, Pb and U, a significant difference in their contents can be
228 observed between samples containing illite (higher amounts of Ni and Pb, lower content of U) and
229 those containing smectites (higher quantity of U, lower levels of Ni and Pb).

230 If we consider that all the investigated clays consist of a significant (and variable) non-clay
231 component, and that in most of the samples the clay fraction contain mixtures of four major groups

232 of phyllosilicates (smectites, illite, kaolinite and chlorites), it is extremely hard to find a clear
233 correlation between mineralogical composition and bulk chemistry. This is even more evident if we
234 keep in view that most of the clay minerals are characterized by variations in chemical composition
235 involving substitutions of Al for Si in tetrahedral cation sites and Al, Fe, Mg and Li in octahedral
236 cation sites. These substitutions cause net positive charge deficiency balanced by exchangeable
237 cations (e.g., Na, Ca, Mg), and bond weakness can allow water and other polar molecules to enter
238 between layers, leading to expansion of the mineral structure. The heterogeneity of smectites, illites
239 and chlorites both structural and chemical, has been extensively reported in literature (e.g. Bailey,
240 1980; Srodon, 1980; Christidis and Duhnam, 1993, 1997; Gaudin et al., 2004).

241 A significant correlation between mineralogy and chemistry emerges only from the sample AR9,
242 which is composed by ~90% of clay fraction, and this latter is dominated by kaolinite. This clay
243 type has a structure in which a tetrahedral silica sheet alternates with an octahedral alumina sheet,
244 with little or no substitution, and the charges within the structural unit are balanced, having
245 consequently low cation-exchange capacities and a chemical formula very close to the ideal
246 $\text{Al}_2(\text{Si}_2\text{O}_5)(\text{OH})_4$. Accordingly, this sample is higher in Al and Si, and very poor in other major
247 elements. However, in terms of trace elements, this sample presents important anomalies, showing
248 maximum contents of Zn, As, Ba, La, Pb and Th.

249

250 *Comparison between investigated clays and average crustal clays*

251 Comparing to the average crustal clays, almost all the investigated clays are generally lower in Si,
252 Al, Ti and Fe contents, while they have equal contents of other major- and trace-elements (Figs. 3
253 and 4). Nonetheless, some samples show substantial differences. As example, all samples from the
254 group 1 are enriched in Ca, Mn, Ni and Sr, while AR4 sample (from illite-bearing group 2) is
255 enriched in K, Zn, As and Pb. Pure smectite samples (group 3), especially AR1, tend to have
256 contents always lower than the average crustal clays, whereas the kaolinite-rich AR9 sample is
257 notably enriched in Zn, As, Ba, La, Pb and Th.

258 In order to understand if the studied clays may contain chemical elements in abnormal amounts, the
259 concentrations of selected elements in the investigated clay samples were compared with the
260 average concentration of the same elements in typical crustal clays (Fig. 5), as reported in literature
261 (Pettijohn, 1957; Turekan and Wedephol, 1961; Mason and Moore, 1982; Gromet et al., 1984). In
262 the spider diagram of Fig. 5, when an element ratio normalized to the average crustal clay is >2 , the
263 element is considered to be enriched and when it is <0.5 it is considered to be depleted.

264 As a general view, the chemical compositions of the studied clays are in agreement with those
265 reported for a crustal clays. However, if we look at the data in more detail significant differences
266 can be pointed out. As example, all the studied clays show some common anomalies, such as
267 depletion in Cu and La (up to 0.2 times the average crustal clay contents). Regarding the group 1
268 samples, all clays have very similar patterns with depletion in Cu, As, Ba, La, Nd, U and Th,
269 whereas they show enrichments in Ni (up to 2.5 times). Samples of group 2 display different
270 patterns: AR12 and AR15 are very similar and are not enriched in any trace element, while AR4
271 (the illite-richest sample) shows enrichments in As (2.3 times) and Rb (3.5 times). Group 3 samples
272 are generally depleted in almost all elements, excluding U (up to 2 times) and Ba (but only for AR7,
273 the smectites-richest sample). No trace element is enriched in sample AR3, while AR9 (the
274 kaolinite-bearing sample) shows enrichments in Zn (2.4 times), As (2.8 times), Ba (2.7 times) and
275 Pb (3.3 times).

276 Most of the clay samples examined in this study contain relatively high amounts of some trace
277 elements, which can be related to (i) the adsorption by the clay minerals, (ii) impurities in the
278 structure of micas and clay minerals, or (iii) possible contamination during manufacturing and
279 commercialization processes. Anyhow, the health impact of certain trace elements could be
280 considerable. According to the chemical limitations reported in the EC Regulation 1223/2009 (EC
281 2009), in the EU Pharmacopeia of 2011 and in the US Pharmacopeia of 2009 in the field of health
282 (U.S. Pharmacopoeia 32-NF 27, 2009), great attention needs to be drawn to the amount of some

283 metals (e.g. Ni, Pb, Cr, As and others), when present. More specifically, some of the studied
284 samples contain trace elements whose concentration is significantly higher than the allowable limit.

285

286 **Concluding remarks**

287 This study has investigated the mineralogical and chemical compositions of some natural clays used
288 in pharmaceutical and cosmetic applications. Analysis from XRPD indicate that all samples are not
289 pure clays being characterized by the presence of a significant non-clay fraction dominated by
290 calcite and quartz, and to a minor extent by dolomite, feldspars and gypsum. The clay fraction is
291 composed by a very diverse set of clay minerals represented by illite, smectites, kaolinite and
292 chlorites. The more represented samples are green ‘mixed’ clays being composed of smectites +
293 illite + chlorites; compared to the average crustal clays, they are several times enriched in Ni and Sr.
294 The green illite-bearing samples are enriched in Rb and As, while the smectite-bearing samples
295 (both brown and white in color) are depleted in almost all the trace elements. Therefore, they
296 represent the more suitable sample to be commercialized. On the contrary, the white kaolinite-rich
297 sample is the most enriched in Zn, As, Ba, La, Pb and Th, and thus it is the most hazardous product.
298 These results show that natural clays available in the market vary considerably in their
299 mineralogical and chemical compositions. Then, their potential risks to human health can only be
300 determined on a detailed, case by case study.

301

302 **Acknowledgements**

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304 **References**

305 Bailey, S.W., 1980. Structure of layer silicates. In: Brindley, G.W., Brown, G. (Eds.), Crystal
306 Structures of Clay Minerals and their X-ray Identification. Mineralogical Society, London, pp.
307 1-123.

- 308 Bergaya, F., Lagaly, G., Vayer, M., 2006. Cation and anion exchange. In: Bergaya, F., Theng,
309 B.K.G., Lagaly, G. (Eds.), Handbook of Clay Science, Developments in Clay Science Series
310 Volume 1. Elsevier Amsterdam, pp. 979-1001.
- 311 Biscaye, P.E., 1964. Distinction between kaolinite and chlorite in recent sediments by X-ray
312 diffraction. *American Mineralogist* 49, 1282-1289.
- 313 Biscaye, P.E., 1965. Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean
314 and adjacent seas and oceans. *Geological Society of America Bulletin* 76, 803-832.
- 315 Brown, G., Brindley, G.W., 1980. X-ray Diffraction Procedures for Clay Mineral Identification. In:
316 Brindley, G.W., Brown, G. (Eds.), *Crystal Structures of Clay Minerals and their X-ray*
317 *Identification*. Mineralogical Society, London, pp. 305-360.
- 318 Carretero, M.I., Pozo, M., 2009. Clay and non-clay minerals in the pharmaceutical industry. Part I.
319 Excipients and medical applications. *Applied Clay Science* 46, 73-80.
- 320 Carretero, M.I., 2002. Clay minerals and their beneficial effects upon human health. A review.
321 *Applied Clay Science* 21, 155-163.
- 322 Carretero, M.I., Gomes, C., Tateo, F., 2006. Clays and human health. In: Bergaya, F., Theng,
323 B.K.G., Lagaly, G. (Eds.), Handbook of Clay Science, Developments in Clay Science Series
324 Volume 1. Elsevier Amsterdam, pp. 717-741.
- 325 Choy, J.H., Choi, S.J., Oh, J.M., Park, T., 2007. Clay minerals and layered double hydroxides for
326 novel biological applications. *Applied Clay Science* 36, 122-132.
- 327 Christidis, G., Dunham, A.C., 1993. Compositional variations in smectites Part I. Alteration of
328 intermediate volcanic rocks. A case study from Milos Island, Greece. *Clay Minerals* 28, 255-
329 273.
- 330 Christidis, G., Dunham, A.C., 1997. Compositional variations in smectites: Part II. Alteration of
331 acidic precursors. A case study from Milos Island, Greece. *Clay Minerals* 32, 253-270.

332 EC (European Commission) (2009) Regulation No 1223/2009 of the European Parliament and of
333 the Council of 30 November 2009 on Cosmetic Products. Official Journal of the European
334 Union L342, 59-209.

335 Gaudin, A., Grauby, O., Oack, Y., Decarreau, N.A., Petit, S., 2004. Accurate crystal chemistry of
336 ferric smectites from the lateritic nickel ore of Murrin Murrin (Western Australia). I. XRD and
337 multi-scale chemical approaches. *Clay Minerals* 39, 301-315.

338 Gomes, C., Silva, J., 2007. Minerals and clay minerals in medical geology. *Applied Clay Science*
339 36, 4-21.

340 Gomes, C., 2003. How minerals are important for human health. In: Ferreira, M.R.P. (Ed.), *A*
341 *Geologia de Engenharia e os Recursos Geológicos*. Imprensa da Universidade, Coimbra, pp.
342 379-390.

343 Grim, R.E., 1968. *Clay Mineralogy*. McGraw-Hill, New York.

344 Gromet, L.P., Dymek, R.F., Haskin, L.A., Korotev, R.L., 1984. The North American shale
345 composite. Its compilation, major and trace element characteristics. *Geochimica et*
346 *Cosmochimica Acta* 48, 2469-2482.

347 Guggenheim, S., Martin, R T., 1995. Definition of clay and clay mineral: Joint report of the AIPEA
348 Nomenclature and CMS Nomenclature Committees. *Clays and Clay Minerals* 43(2), 255-256.

349 Lagaly, G., 1989. Ingredients of flow of kaolin and bentonite dispersions. *Applied Clay Science* 4,
350 105-123.

351 López Galindo, A., Viseras, C., 2004. Pharmaceutical and cosmetic applications of clays. In:
352 Wypych, F., Satyanarayana, K.G. (Eds.), *Clay Surfaces. Fundamentals and Applications*.
353 Elsevier ,Amsterdam, pp. 267-289.

354 López Galindo, A., Viseras, C., Cerezo, P., 2007. Compositional, technical and safety specifications
355 of clays to be used as pharmaceutical and cosmetic products. *Applied Clay Science* 36, 51-63.

356 Mascolo, N., Summa, V., Tateo, F., 1999. Characterization of toxic elements in clays for human
357 healing use. *Applied Clay Science* 15, 491-500.

- 358 Mason, B., Moore, C.B., 1982. Principles of Geochemistry. Wiley. New York.
- 359 Moore, D.M., Reynolds, R. C., 1997. X-Ray Diffraction and the Identification and Analysis of Clay
360 Minerals, 2nd edition. Oxford University Press, New York.
- 361 Murray, H.H., Keller, W.D., 1993. Kaolins, kaolins and kaolins. In: Murray, H.H., Bundy, W.,
362 Harvey, C. (Eds.), Kaolin Genesis and Utilization. Boulder, Colorado, pp. 1-24.
- 363 Patel, N.K., Kennon, L., Levinson, R.S., 1986. Pharmaceutical suspensions. In: Lachman, L.,
364 Liebennan, H.A., Kanig, J.L. (Eds.), The Theory and Practice of Industrial Pharmacy, 3rd
365 edition. Lea & Febiger, Philadelphia, USA, pp. 479-501.
- 366 Pettijohn, F.J., 1957. Sedimentary Rocks, 2nd edition. Harper & Row, New York.
- 367 Reynolds, R.C., 1980. Interstratified clay minerals. In: Brindley, G.W., Brown, G. (Eds.), Crystal
368 Structures of Clay Minerals and their X-ray Identification. Mineralogical Society, London, pp.
369 249-303.
- 370 Roselli, C., Desideri, D., Cantaluppi, C., Mattioli, M., Fasson, A., Meli, M.A., 2015. Essential and
371 toxic elements in clays for pharmaceutical and cosmetic use. Journal of Toxicology and
372 Environmental Health Part A 78, 1-9.
- 373 Setti, M., Marinoni, L., Lopez-Galindo, A., 2004. Mineralogical and geochemical characteristics
374 (major, minor, trace elements and REE) of detrital and authigenic clay minerals in a Cenozoic
375 sequence from Ross Sea, Antarctica. Clay Minerals 39, 405-421.
- 376 Silva, P.S.C., Oliveira, S.M.B., Farias, L., Favaro, D.I.T., Mazzilli, B.P., 2011. Chemical and
377 radiological characterization of clay minerals used in pharmaceuticals and cosmetics. Applied
378 Clay Science 52, 145-149.
- 379 Srodon, J., 1980. Precise identification of illite/smectite interstratifications by X-ray powder
380 diffraction. Clays and Clay Minerals 28, 401-411.
- 381 Summa, V., Tateo, F., 1998. The use of pelitic raw materials in thermal centres: mineralogy,
382 geochemistry, grain size and leaching test: examples from the Lucania area (southern Italy).
383 Applied Clay Science 12, 403-417.

384 Tateo, F., Summa, V., 2007. Element mobility in clays for healing use. *Applied Clay Science* 36,
385 64-76.

386 Tateo, F., Summa, V., Giannossi, M.L., Ferraro, G., 2006. Healing clays: Mineralogical and
387 geochemical constraints on the preparation of clay water suspension (argillic water). *Applied*
388 *Clay Science* 33(3-4), 181-194.

389 Thorez, J., 1975. *Phyllosilicates and clay minerals - a laboratory handbook for their x-ray*
390 *diffraction analysis*. G. Lelotte, Dison, Belgium.

391 Thorez, J., 1976. *Practical Identification of Clay Minerals*. G. Lelotte, Dison, Belgium.

392 Turekian, K. K. & Wedephol, K. H. (1961) Distribution of the elements in some major units of the
393 earth's crust. *Geological Society of America Bulletin* 72, 175-192.

394 Velde, B., 1995. *Origin and Mineralogy of Clays: Clays and the Environment*. Springer-Verlag,
395 Berlin.

396 Viseras, C., 1997. *Caracterización de distintos materiales de origen mineral para su empleo en la*
397 *elaboración de medicamentos: esmectitas, paligorskitas, sepiolitas*. PhD Thesis, Universidad de
398 Granada, 250 pp.

399 Viseras, C., Aguzzi, C., Cerezo, P., Lopez-Galindo, A., 2007. Uses of clay minerals in semisolid
400 health care and therapeutic products. *Applied Clay Science* 36, 37-50.

401 Yebra, A., 2000. *Influencia de la mineralogía, quimismo y textura en las aplicaciones básicas*
402 *industriales de la sepiolite*. PhD Thesis, Universidad de Granada, 300 pp.

403

404 **Table captions**

405 **Tab. 1.** Semi-quantitative percentages of mineral of the investigated clays (bulk compositions). Qz
406 quartz, Ca calcite, F feldspars, Do dolomite, Gy gypsum, Cr cristobalite. *pH values are from
407 Roselli et al. (2015).

408
409 **Tab. 2.** Semi-quantitative results on clay minerals of the $<2\mu\text{m}$ fraction of the investigated clays,
410 based on profile fit-derived peak areas and Biscaye's (1965) weight factors. Sm smectite group, Qz
411 quartz, I/M illite/mica, Chl chlorite group, Ka kaolinite.

412
413 **Figure captions**

414 **Fig. 1.** Representative XRD patterns of the investigated samples (bulk compositions). Sm smectite
415 group, Qz quartz, I/M illite/mica, Chl chlorite group, Ca calcite, F feldspars, Do dolomite, Ka
416 kaolinite.

417
418 **Fig. 2.** Representative XRD patterns of the investigated samples ($<2\mu\text{m}$ clay fraction). Sm smectite
419 group, I/M illite/mica, Chl chlorite group, Ka kaolinite.

420
421 **Fig. 3.** Selected major elements vs silica diagrams of the investigated clays. Average crustal clays
422 data are from Pettijohn (1957), Turekan and Wedephol (1961), Mason and Moore (1982) and
423 Gromet et al. (1984).

424
425 **Fig. 4.** Selected trace elements vs silica diagrams of the investigated clays. Average crustal clays
426 data are from Pettijohn (1957), Turekan and Wedephol (1961), Mason and Moore (1982) and
427 Gromet et al. (1984).

428
429 **Fig. 5.** Spider diagrams of the selected elements for the investigated clays, normalized to the
430 average crustal clay (according to Pettijohn 1957; Turekan and Wedephol 1961; Mason and Moore
431 1982; Gromet et al. 1984).