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► To cite this version:

Julie Chenot, Renaud Jaunatre, Elise Buisson, Fabrice Bureau, Thierry Dutoit. Impact of quarry exploitation and disuse on pedogenesis. *CATENA*, 2018, 160 (160), pp.354-365. 10.1016/j.catena.2017.09.012 . hal-01790691

HAL Id: hal-01790691

<https://hal.science/hal-01790691v1>

Submitted on 14 May 2018

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Impact of quarry exploitation and disuse on pedogenesis

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Abstract

Quarrying represents one of the oldest and most important human activities; the impacts of which have largely influenced vegetation and landscape. Despite its character as a vital and non-renewable resource, the soil has been poorly studied with regard to either the impact resulting from the exploitation of quarries or its restoration after exploitation. In the plain of La Crau (south-eastern France), numerous dry alluvial quarries were exploited in the 1970s. Their exploitation lasted about ten years and they were then rapidly abandoned. At that time, there was no legal obligation to restore sites after their abandonment. In this context, following various modes of exploitation (e.g. exploitation depth), various rehabilitation options were implemented: no rehabilitation, topsoil transfer, deposits of anthropogenic materials. The absence of legislation consequently resulted in heterogeneous areas after their abandonment. Today, we have the benefit of 35 years of hindsight on the dynamics of these ecosystems resulting from these exploitation modes and rehabilitation options and thus various questions arise: (1) Did the diversity of the modes of exploitation result in heterogeneous soils 30 years after abandonment? (2) At what stage of pedogenesis are the soils created in the abandoned quarries? (3) Did the various rehabilitation options have an impact on the traces of biological activity in the soils of the quarries? (4) Is it possible to identify methods of rehabilitation of quarries that would favour the rehabilitation of the soils and the recolonisation of the plant cover in order to improve the techniques in use or to propose alternative methods? The study of soil profiles (with a special focus on biological activity of animals and plants) and soil physico-chemical analyses (pH, CaCO₃, C, N, C:N ratio, CEC, exchangeable K⁺, plant available P and fine soil particle contents) made it possible to study these questions. Our results confirm that all the soils resulting from the former exploitation modes and rehabilitation options of the quarries present their own specific characteristics (upper soil layer fertility, soil profile vertical organization) which remain very different, even after 30 years, from the characteristics of the destroyed reference soil ecosystem. Pedogenetic processes are very slow or even blocked by the recurrent action of certain environmental parameters. In terms of ecological rehabilitation, only topsoil transfers undertaken under good conditions (same soil thickness as the reference steppe and no contact with the phreatic zone) have allowed to restore most of the physical and chemical properties recorded close to the reference ecosystem soil.

Key-words: ecological rehabilitation, Haplic Cambisol, Hyperskeletal Leptosols, soil profiles, Technosols

1. Introduction

47 In the early 21st century, between one third and half of the earth's surface has been transformed by
48 human actions (Vitousek *et al.* 2008), 85% of it in Europe (Primack *et al.*, 2012). These
49 transformations, still on the increase, are mainly driven by economic and demographic imperatives,
50 associated with the intensive exploitation of the basic resources required for human needs (agriculture,
51 industry, fisheries, international trade, *etc.*) (Balmford *et al.*, 2002). Among these changes in use,
52 mining represents one of the oldest and most important human activities (Larson *et al.*, 2006). Today,
53 the large number of disused quarries or those in the process of closing down in many countries
54 represent a challenge for the restoration of these severely degraded habitats (Bradshaw, 1997; Darwish
55 *et al.*, 2011; Mouflis *et al.*, 2008). In Europe, more than 2.7 billion tons of aggregates are produced
56 each year in 25 000 quarries spread throughout Europe (*Union Européenne des Producteurs de*
57 *Granulats*, 2015). In contrast to underground mines, the impact of which may be more localised
58 (Bradshaw, 1997), the exploitation of opencast quarries has a direct impact on the environment, and in
59 particular on the vegetation and the soil, since it leads inevitably to a profound alteration of the
60 composition and / or structure of the soil, or even its complete disappearance. The processes involved
61 in the evolution of highly anthropized soils have yet to be specifically addressed within the soil
62 scientist community. The nature of pedogenetic processes in these soils may be very similar to those in
63 natural soils. However, the presence of purely anthropogenic materials on soil pedogenetic evolution
64 and the nature of pedogenetic processes remain to be explored (Huot *et al.*, 2014).

65
66 The studies carried out on the environmental impact of quarries have mainly focused on the
67 vegetation, without taking into account the edaphic conditions (De Deyn *et al.*, 2003). The restoration
68 of these sites after exploitation has thus been mainly focused on the ecosystem compartment that is
69 most often used as the main environmental criterion for assessing the success of the restoration (Koch,
70 2007). Despite its character as a vital and non-renewable resource (Van-Camp *et al.*, 2004), the soil
71 has been very little studied with regard to either the impact resulting from the exploitation of quarries
72 or its restoration after exploitation. To determine whether we should intervene after exploitation
73 ceased and re-establish the functioning of the ecological communities in the long term, it is necessary
74 to take into account all the compartments of the ecosystem (Bradshaw and Hüttl, 2001) and in
75 particular the soil (Heneghan *et al.*, 2008). Studies should not be restricted to one type of exploitation
76 for a given surface area, but should integrate the diversity of the types of exploitation and post-
77 exploitation redevelopment that are often encountered within the same quarry over time or in a series
78 of quarries situated on the same geopedological unit (Dana and Mota, 2006; Duque *et al.*, 1998; Yuan
79 *et al.*, 2006).

80
81 The plain of La Crau (south-eastern France), described as a Mediterranean pseudo-steppe, presents a
82 range of soil, flora, fauna and ecosystem characteristics that confer on it a heritage character (Tatin *et*
83 *al.*, 2013). Much of this plain is classified as a natural reserve and the protection of its habitats and of
84 the associated species has been in force since 2001 (Beltrando, 2015). Prior to the introduction of this
85 protection, numerous dry alluvial quarries were exploited there in the 1970s to build an industrial port.
86 They resulted in the destruction of part of the original ecosystem (Buisson and Dutoit, 2006). Their
87 exploitation lasted about ten years and they were then rapidly abandoned. At that time, there was no
88 legal obligation to restore the site after ceasing use. In this context, various rehabilitation options were
89 established. Techniques for soil transfer were thus implemented (Bulot *et al.*, 2014), mainly for the
90 purposes of landscaping and safety. In contrast, in other areas, no rehabilitation operation was
91 undertaken, leaving the environment completely bare immediately after exploitation (Chenot *et al.*,
92 2017). This absence of legislation consequently resulted in a pattern of heterogeneity of these areas
93 after the end of exploitation. Today, we have the benefit of 35 years of hindsight on the dynamics of
94 these ecosystems resulting from the cessation of exploitation of the quarries.

95

96 Given these specificities regarding the exploitation, various questions arise: (1) Did the diversity of the
97 modes of exploitation result in a pattern of heterogeneity of the soils 30 years after ceasing use? (2) At
98 what stage of pedogenesis are the soils created in the abandoned quarries? (3) Did the various
99 rehabilitations have an impact on the traces of biological activity in the soils of the quarries? (4) Is it
100 possible to identify methods of rehabilitation of quarries that would favour the rehabilitation of the
101 soils and recolonisation of the plant cover in order to improve the techniques in use or to propose
102 alternative methods? To answer the questions, the various soils taken from a series of abandoned dry
103 alluvial quarries over about thirty years in south-eastern France were described by means of soil
104 profile pits and measurement of physical and chemical parameters. They were then compared with the
105 soils (Cambisol types) that existed before the exploitation of the quarries and which still exist in the
106 vicinity in the landscape matrix constituted of a Mediterranean sub-steppe grassland (Bouteyre and
107 Duclos, 1994). Finally, the coarse fragment cover, plant cover and traces of biological activity
108 observed in the soil profiles (presence of earthworm galleries and roots) characterising the various
109 soils were also compared.

110 Our hypotheses were as follows: (1) the diversity in the modes of exploitation resulted in a high
111 heterogeneity of the soils encountered in former quarries; (2) the majority of the soils created were
112 rejuvenated artificial soils and / or young intra-zonal type soils bearing little resemblance to the
113 reference steppe soil, except in cases where re-spreading of the original soil was undertaken after
114 exploitation ceased; (3) these alterations have important implications with regard to biological activity
115 traces in soil profiles pits and the cover of the plants spontaneously colonising the soil surface of these
116 former quarries, even in the long term (several decades).

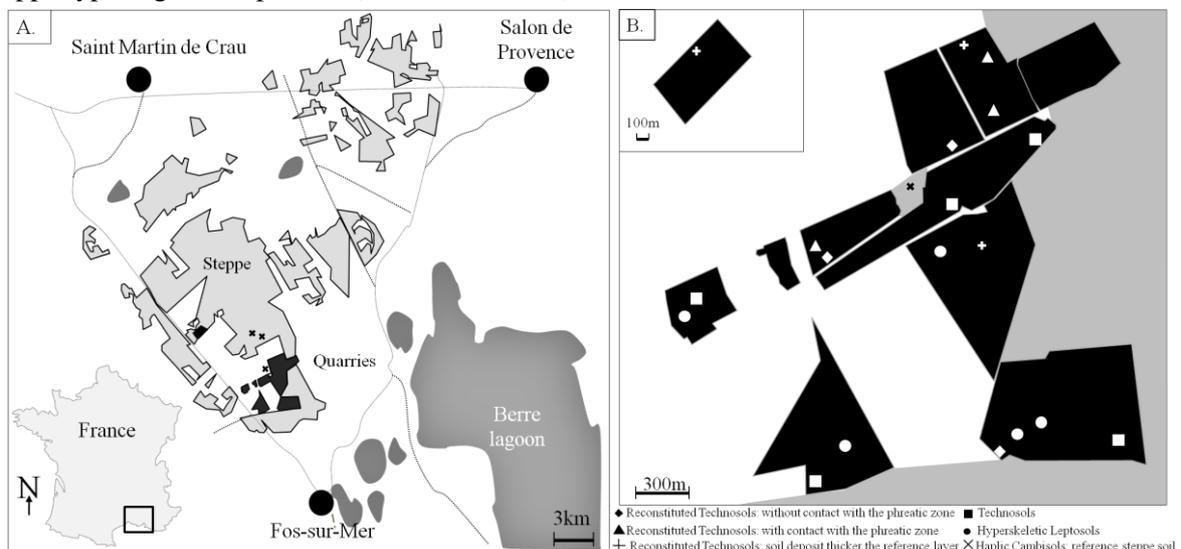
117

118 2. Material and methods

119 2.1. The study site

120 Our study site is located in the south of the plain of La Crau ($43^{\circ}31'36.77''N$, $4^{\circ}53'04.50''E$), south-
121 eastern France (Bouches-du-Rhône) (Fig. 1.A). The plain is characterised by a unique natural habitat
122 classified in 1990 as a Natura 2000 Special Protection Zone, including areas of Mediterranean sub-
123 steppe grassland and disused sites (agricultural, industrial or military). Originally covering more than
124 60 000 ha, the agricultural activities (irrigated meadows, intensive fruit farms, market gardens, etc.),
125 industrial activities (logistical platforms, quarries, etc.) and military activities (ammunition dumps,
126 military airport, etc.) destroyed more than 80% of it, and today, only 10 500 ha of non-degraded
127 steppe-type vegetation persists (Tatin et al., 2013).

128



128

129 Fig. 1. Location of the study site and soil profiles (A) Location of the plain of La Crau area in France
130 (60 000 ha) and location of the remnant patches of steppe (grey) (10 000 ha) and the former quarries
131 studied (black) (296 ha); (B) Location of soil profiles of the different rehabilitation treatments.

132

133 2.1.1. *The climate of the La Crau plain*

134 The La Crau plain presents all the characteristics of a Mediterranean climate, with hot, dry summers,
135 relatively mild winters and high solar irradiation. Rainfall is rare but abundant, and is mainly
136 concentrated in the autumn, with more than 50% of the annual total (541 mm/year) (Tatin et al., 2013).
137 The climate is also characterised by the “*Mistral*”, a very frequent, strong cold wind. Its occurrence
138 entails exceptionally high annual rates of solar irradiance (3000 hours/year), enhancing
139 evapotranspiration and thus the summer drought. In winter, it also contributes to lower the
140 temperature.

141

142 2.1.2. *The soil of the La Crau plain*

143 The geographical area of the La Crau plain corresponds to the former fossilised bed of the Durance,
144 generated by deposits washed down during the Quaternary Period (Molliex et al., 2013). The La Crau
145 plain has been formed by alluvial deposits, siliceous pebble and gravel type with sandy matrix
146 between - 2 million years and - 30 000 years, the date of the capture of the Durance by the Rhône to
147 the north of the plain, which then dried up. The thickness of the alluvial deposits ranges between 5 and
148 35 metres, depending on the location. The soil of the La Crau plain has been identified as
149 Mediterranean red soil (Commission de Pédologie et de Cartographie des Sols, 1967), also referred to
150 as Haplic Cambisol (Calcaric) according to the World Reference Base for Soil Resources (IUSS
151 Working Group WRB, 2015). Developed on the ancient stony alluvium of the Durance, these clay-
152 loam soils present between 40 and 80 cm depth a conglomerate or a calcareous crust. This crust results
153 from the dissolution of calcareous stones and the leaching of calcium which is then precipitated in
154 depth (Duclos, 1994). The thickness of this crust may vary between 1 and 5 m, and there may be
155 several layers within the thickness of the alluvium.

156

157 Such soils are frequently encountered in stable geomorphological situations that have enabled their
158 development over long periods of time (several hundreds of millions of years) (Tatin et al., 2013). The
159 solum of the La Crau plain is said to be 'truncated' as the topsoil normally rich in fine elements of the
160 silt type is greatly reduced, or even non-existent, a phenomenon resulting from wind erosion
161 concomitant with the deposition. This phenomenon dates from around 10 000 years ago, and exposed
162 the siliceous stones which may then cover more than 50% of the soil surface (Devaux et al., 1983).

163

164 2.1.3. *The vegetation of the La Crau plain*

165 Under the combined effect of climate, multi-secular sheep grazing and specific soil conditions, a
166 particular plant community has developed, resulting in a regressive or allogenic plant succession of
167 thousands of years. It is a plant community described as a sub-steppic grassland of the Mediterranean
168 and belonging to the association *Asphodelietum fistulosii* (Molinier and Tallon, 1950), dominated by
169 *Brachypodium retusum* (Pers.) P. Beauv, *Thymus vulgaris* L. and *Asphodelus ayardii* Jahand and
170 Marie. This plant community is interesting in terms of species richness, composition and diversity
171 (Badan et al., 1995; Cherel, 1988; Henry, 2009). There are on average 40 to 50 species of plants per
172 four square meters, among which 50% are annuals (Römermann et al., 2005).

173

174 2.1.4. *The quarries in the La Crau plain*

175 Our study site has the particular feature of presenting 296 ha of dry alluvial quarries (exploitations of
176 sand, gravel and pebbles) which were mined during the 1970s for the construction of the industrial

177 port zone of Fos-sur-Mer (Fig. 1) (Devaux et al., 1983). This activity resulted in the destruction of
178 around 300 ha of an original steppe ecosystem (Buisson and Dutoit, 2006). All these quarries were
179 abandoned during the 1980s (Chenot et al., 2017). However, at that time, there was no legal obligation
180 to restore the site after the cessation of mining (DITR, 2005; European Parliament, 2014; UNEP et al.,
181 2005). Consequently, various modes of redevelopment were adopted, ranging from simple
182 abandonment (exploited substrate left bare), to the replacement of the topsoil removed and stockpiled
183 during the period of exploitation, of local backfill (unsold stocks of stones, sand, silt and clay resulting
184 from the decantation processes, etc.) or from imported spoil (inert rubble from deconstruction, etc.),
185 with all the possible combinations. Another source of heterogeneity also derives from the depth of
186 mining. If this is currently limited to 5 m depth to protect the phreatic zone, depths of more than 9 m
187 were reached thirty years ago, exposing the water table in certain quarries.

188

189 2.2. Description and analyses of soil profiles

190 In order to identify the various types of soil present in the quarries and in the steppe, a description of
191 the solum has been undertaken to analyse soil development and disturbances that have occurred. For
192 this purpose pedological pits were described in March 2015 after excavation with a mechanical digger
193 (Fig. 1.B). The pits are situated in the areas that the digger has not been driven over in order to avoid
194 the potential compacting of the soil by the passage of this heavy equipment (Baize and Jabiol, 2011).
195 In all, 20 pedological pits measuring around 1m² with a depth of 0.5 to 1.5 m were dug in
196 homogeneous zones defined on the basis of aerial photographs, the vegetation and the knowledge of
197 the quarry workers regarding former modes of exploitation. The excavation was halted once the
198 subsoil (Durancian pebbles) or the level of the phreatic zone was reached.

199

200 Four potential situations were thus identified prior to digging the pits (Table 1): (1) reference steppe
201 soil; (2) reconstituted soils subdivided into 3 categories i.e. (2.1) reconstituted soils with thickness
202 identical to the reference soil (40 cm) without contact with the phreatic zone, or (2.2) with contact with
203 the phreatic zone; (2.3) soil deposit thicker than the reference soil layer (>40 cm); (3) soil with
204 deposits of anthropogenic materials, and finally (4) raw bedrock left on the surface. A minimum of 3
205 soil profiles were replicated for each type of soil in the quarries and in the reference steppe (Table 1).
206 The soil profiles were described according to the standard procedures using the STIPA 2000 data
207 sheets of the *Institut National de la Recherche Agronomique* (Falipou and Legros, 2002)
208 recommended by the *Association Française d'Etudes des Sols* (Baize and Jabiol, 2011). Then, the
209 denomination of the soil profile and the pedological layers was first done according to the *Référentiel*
210 *pédologique* 2008 (Baize and Girard, 2008) and then according to the *World Reference Base for Soil*
211 *Resources* (IUSS Working Group WRB, 2015).

212

213 The physical and chemical analyses of the soil were carried out on twenty-nine 200 g soil samples
214 collected in the disused quarries in March 2015. To do this, samples were extracted in the first ten
215 centimetres of the upper soil / material layer. The sample collection was replicated at least four times
216 for each type of soil previously identified on the basis of the soil profiles (Table 1).

217

218 Each sample was dried and sieved with a 2 mm mesh sieve. The physical-chemical analyses (pH water
219 ratio 1:5 (Thomas, 1996), CaCO₃ using a Bernard calcimeter (Sparks et al., 1996), organic C (Allison,
220 1965) and total N by dry combustion (Bremner, 1996; Dumas, 1831), C:N ratio, Cation Exchange
221 Capacity (CEC) and exchangeable K⁺ by Metson (Metson, 1956; Ciesielski et al., 1997), plant
222 available P (Olsen, 1954) and the particle-size distribution in 5 fractions by the Robinson method
223 without prior decarbonisation (clay (<0.002 mm), fine silt (0.002-0.02 mm), coarse silt (0.2-2 mm),

224 fine sand (0.05-0.2 mm) and coarse sand (0.2-2 mm)) were performed by the soil analysis laboratory
 225 at INRA (*Institut National de la Recherche Agronomique*), Arras.

226

227 Table 1: The different types of soil described in this study and sampling for the various analyses.

Type of soil according to WRB (2015)	Type of soil according to the <i>Référentiel pédologique</i> (2008)	Site specifications	Number of samples for the soil analyses (0-10cm)	Number of soil profiles described	Number of vegetation transects
Haplic Cambisol (Calcaric)	Fersialsols	1. Steppe	5	3	6
Reconstituted Technosols	Reconstituted Anthroposol	2. 40 cm of original soil transfer without contact with the phreatic zone	4	3	4
		3. 40 cm of original soil transfer with contact with the phreatic zone	5	3	3
		4. > 40 cm of transfer of original soil	5	3	3
Technosols	Artificial Anthroposol	5. Deposits of anthropogenic materials	5	5	5
Hyperskeletal Leptosols	Peyrosol	6. Raw bedrock at the surface	5	5	4

228

229 2.3. Measurement of traces of biological activity

230 During the observation of the soil profiles, the traces of biological activity were quantified. They are
 231 good indicators of soil function restoration over the whole profile via exchanges between the different
 232 soil layers (presence of earthworm galleries and roots). The biological activities and in particular the
 233 soil fauna is indeed an integral part of the soil and is indispensable for its development (De Deyn et
 234 al., 2003; Frouz et al., 2007). It is used as an indicator of the quality of the environment, and in order
 235 to determine the actual functioning of the soil, it is necessary to take it into account in soil studies.
 236 Characterised as ecosystem engineers, the earthworms strongly influence the edaphic compartment of
 237 ecosystems (Lavelle et al., 1997). The quality of the soil is related to the density and the activity of the
 238 earthworms, which improve it (Boyer and Wratten, 2010; De Deyn et al., 2003; Frouz et al., 2007;
 239 Pérès et al., 2011). The vegetation is related to these activities since the earthworms aerate the soil and
 240 enable better root development, and thus enhanced growth of the vegetation (Whalley and Dexter,
 241 1994). The roots and the earthworms thus play a key role with regard to the generation of the structure
 242 of the soil and consequently for the quality of the soil (Whalley and Dexter, 1994).

243

244 The traces of the biological activity of animals (earthworms) and plants (roots) have been estimated
 245 visually on the whole series of profiles described on the basis of the estimation grids proposed by
 246 Baize and Jabiol (Baize and Jabiol, 2011). Various parameters have been taken into account and
 247 integrated in the statistical analyses (Appendix A.).

248

249 2.4. Percentages of vegetation and coarse fragments cover

250 The percent cover of the vegetation and of the coarse fragments was visually estimated using 4m²
 251 quadrats in May 2015 at the time of peak productivity (Bourrelly et al., 1983). For each type of soil
 252 and in function of their surface area, 3 to 6 x 100 meters transects were replicated, each composed of 5

253 pseudo-replicated quadrats (Table 1). In each transect, the quadrats were placed more than 10 meters
254 apart in order to avoid any spatial auto-correlation between the quadrats.

255

256 2.5. Data analysis

257 All the data analyses were performed using the statistical software R 2.13.0 (R Development Core
258 Team, 2016) and the packages ade4 (Chessel et al., 2004; Dray and Dufour, 2007; Dray et al., 2007),
259 FactoMineR (Husson et al., 2016), JLutils coupled with Devtools (Hadley and Winston, 2016) vegan
260 (Oksanen et al., 2015), and RColorBrewer (Neuwirth, 2014).

261

262 2.5.1. Analyses of physical and chemical parameters of the soil

263 To characterise the physical and chemical parameters of the various types of soil, a Non-metric Multi-
264 Dimensional Scaling (NMDS) was performed on the variables (6 types of soil \times 29 soil samples). On
265 this NMDS were displayed simultaneously the two physical-chemical elements that best contributed to
266 explain the ordination in the different types of soil studied. Analyses and illustrations were made using
267 the package vegan (Oksanen et al., 2015).

268

269 Furthermore, univariate analyses were performed on each physical and chemical parameter measured
270 in the soils. When the parametric conditions were encountered, we carried out an ANOVA test
271 followed by a Tukey HSD post-hoc test when significant differences were encountered. When the
272 parametric conditions were not met, we used a Kruskal-Wallis non-parametric test followed by post-
273 hoc tests of Wilcoxon with Bonferroni adjustment if a significant difference was detected (Bonferroni,
274 1936).

275

276 2.5.2. Analyses of indices of the presence of biological activity in the soils

277 To describe the mode of assembly of the methods adopted for the study of the presence of biological
278 indicators of activity of earthworms and roots, Multiple Component Analyses (MCA) were performed
279 using the packages ade4 (Chessel et al., 2004; Dray and Dufour, 2007; Dray et al., 2007) and
280 FactoMineR (Husson et al., 2016). Several observations may be identical in the MCA when they
281 correspond to the same combination of modalities. Thus these observations are projected on the same
282 point in the factorial plan. They cannot however be observed by means of a classic representation of
283 the results. For that, the packages JLutils, coupled with Devtools (Hadley and Winston, 2016) were
284 used to represent each point of the MCA by a square proportional to the number of observations.

285

286 2.5.3. Analyses between types of soil, plant cover and coarse fragments cover

287 To test possible correlations between the characteristics of the various types of soil, the plant cover
288 and the coarse fragments cover ($>$ 2mm) at the surface, a Kruskal-Wallis non-parametric test was
289 performed. This was followed by pairwise Wilcoxon tests with Bonferroni adjustment to detect
290 significant differences (Bonferroni, 1936).

291

292 3. Results

293 3.1. Analyses of soil profiles

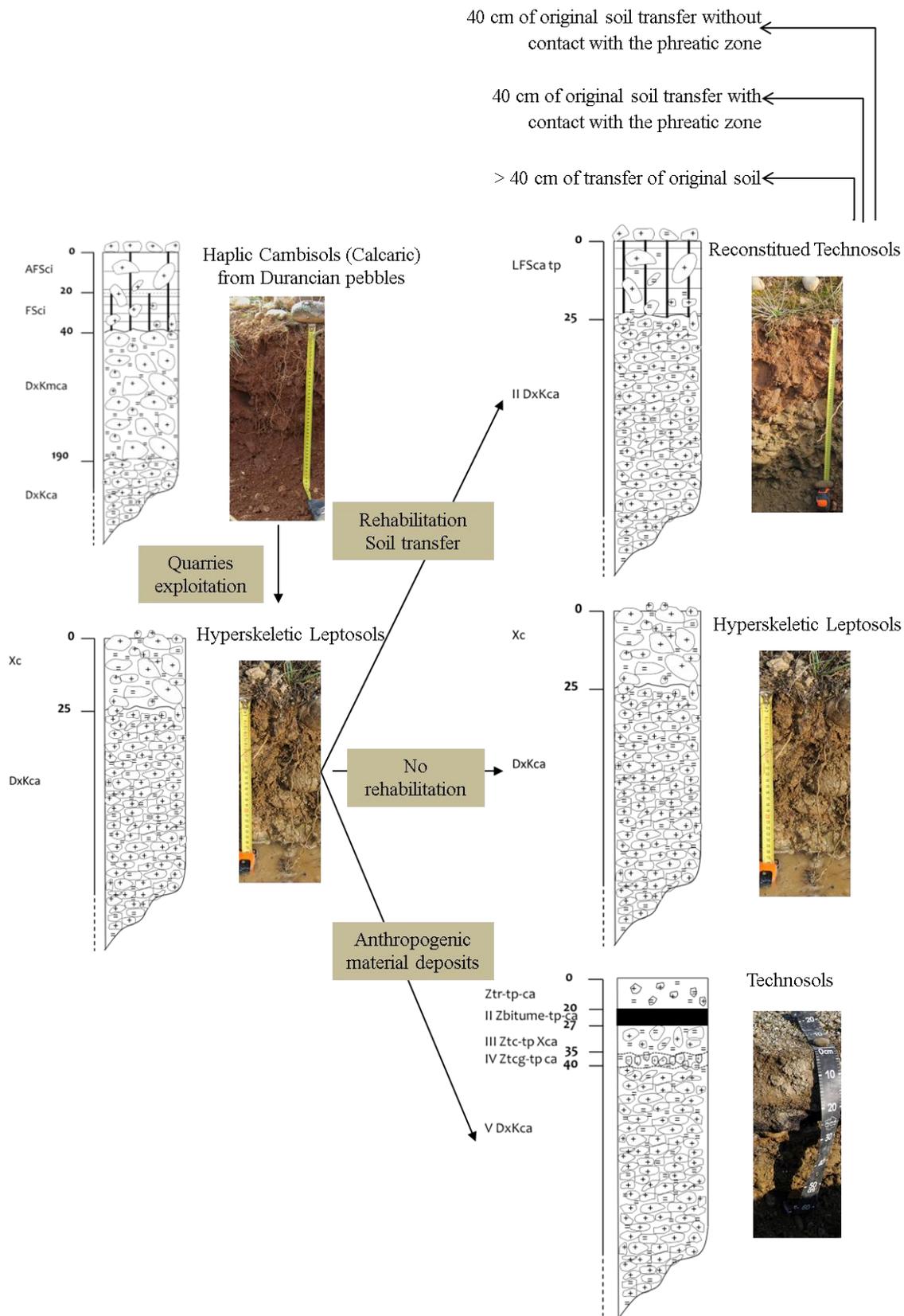
294 The construction of soil profiles at the bottom of the quarries provided the means to sample several
295 types of soil that were highly differentiated and far removed from the reference steppe soil. According
296 to the techniques of quarrying and redevelopment, the soils of the quarries underwent greater or lesser
297 degrees of degradation with regard to their composition and structure and also highly diverse artificial
298 recomposition.

299

300 The exploitation of the quarries involved the destruction of the fersialitic layer (Fs) characteristic of
301 the steppe soil, but also the conglomerate petro-calcareous layer (DxKca) and finally a variable
302 thickness of raw bedrock material composed of alluvium from quarried Durancian pebble. This
303 resulted in Hyperskeletal Leptosols type soils characterised by a single pebble layer (X) more than 10
304 cm thick. It contains more than 60% of coarse fragments, such as pebbles embedded in a sandy matrix
305 type (Fig. 2). Depending on the depth of the quarrying, this soil layer underwent variations in the
306 height of the water table and may in some cases be flooded for periods of a few days to several weeks.
307 A first stage of pedogenesis (on 1 or 2 cm of topsoil) can then be observed in certain cases, enabling
308 the constitution of a 'young' layer in the topsoil (Js) containing small quantities of organic matter
309 (derived in particular from leaves of *Populus* sp. and *Salix* sp.), though without any bio-
310 macrostructuration.

311
312 On this raw bedrock, various anthropogenic materials (earth, asphalt, technological) were deposited
313 and identified in the various pits, either on a single layer, or on several layers deposited directly on the
314 anthropic raw material. From this superimposition result soils referred to as Technosols since they
315 come at 100% from anthropic materials corresponding to "artifacts" in WRB (Fig. 2). These soils may
316 then be constituted from debris (waste materials from the demolition of houses, roads, etc.) or from a
317 hard artificial layer (such as asphalt, concrete, stone, brick, etc., at depth).

318
319 The last type of soil encountered results from the re-spreading of the topsoil removed prior to mining.
320 This soil has been replaced directly on the unexploited geological material (Durancian pebble),
321 whatever the level of the phreatic zone, or on other anthropic materials. This results in reconstituted
322 Technosols of which the transferred layer derives from fersialitic layers (topsoil removed and
323 stockpiled prior to mining). From these reconstituted Technosols, 3 modes may be observed at the
324 sites: i) transfer of soil to a thickness of about 40 cm (similar to the thickness of the original fersialitic
325 layer) without contact with the phreatic zone situated at 9 m depth; ii) transfer of soil to a thickness of
326 about 40 cm with fluctuations of the water table in sectors where the mining was in the vicinity of 9 m
327 depth, and iii) transfer of the soil to a thickness of more than 40 cm (generally more than a metre of
328 the fersialitic layer), corresponding to old mounds of soil stockpiled and simply re-spread after mining
329 ceased (Fig. 2).



330

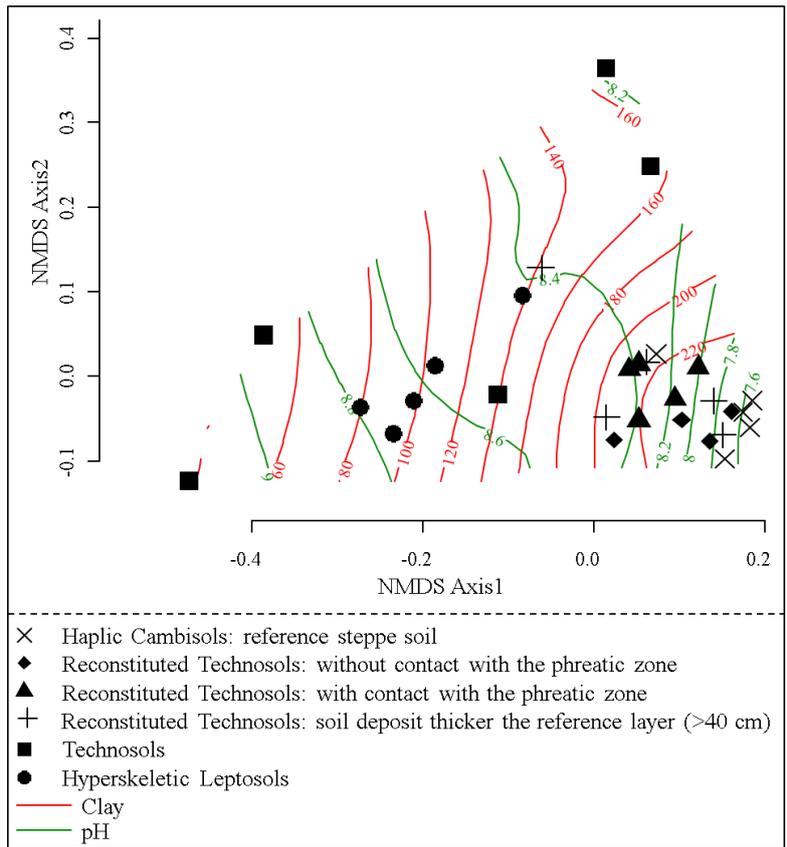
331 Fig. 2: Pictures and schemes of soil profiles of reference soil and the different types of soil derived
 332 from mining according to the various modes of rehabilitation after cessation of exploitation. The
 333 schemas follow the denomination of the *Référentiel pédologique 2008* (Baize and Girard, 2008) for
 334 layers denominations and WRB (2015) for soil denomination, (+) siliceous non altered bedrock; (=)
 335 Calcium carbonate; Clay 2/1 ; Ferric iron accumulation dehydrated.

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3.2. Soils physical and chemical analyses

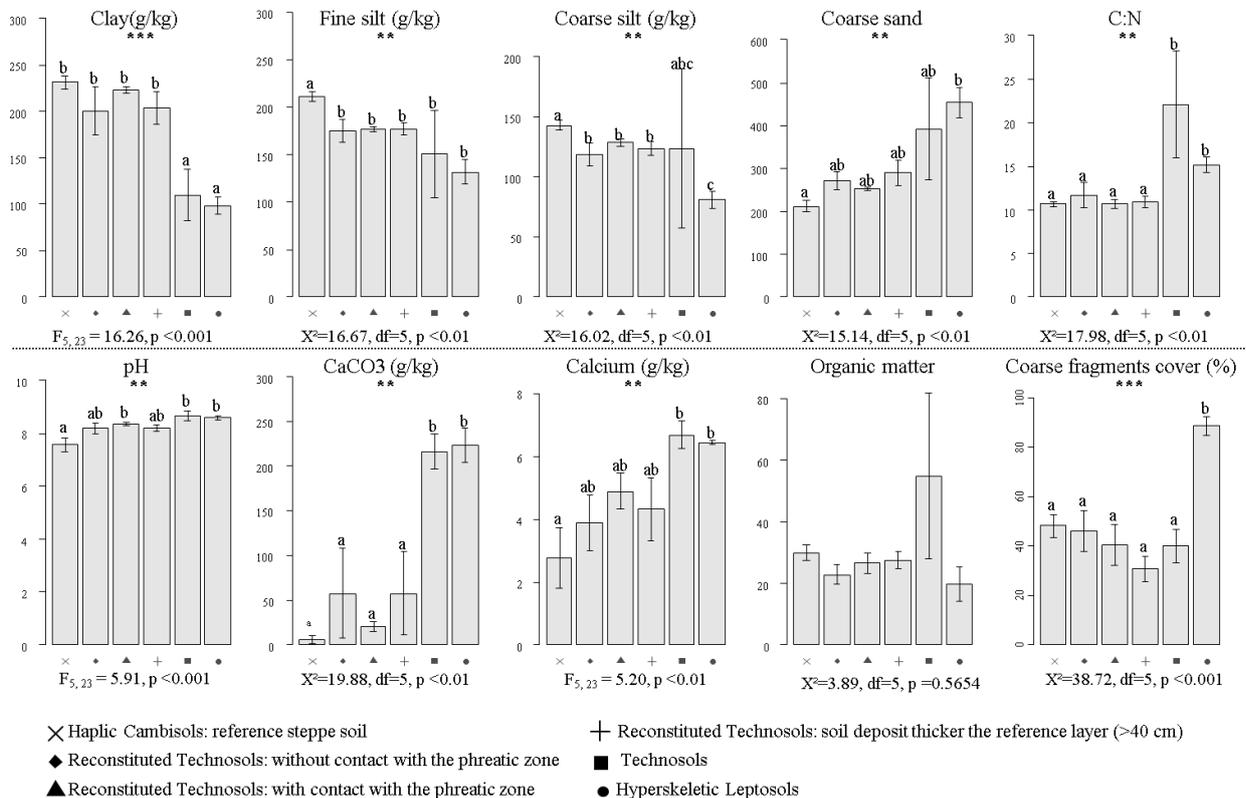
The soils identified during the description of the soil profiles present clear differences in their physical and chemical properties (Fig. 3). The NMDS based on the properties of soils indeed discriminates between the various soils. Axis 1 separates the Haplic Cambisol (steppe) and reconstituted Technosols (soil transfer) from the Hyperskeletal Leptosols. This distinction is explained in part by the quantity of clay, which is significantly greater in the Haplic Cambisol, and a less alkaline pH. In contrast, in the Hyperskeletal Leptosols, the substrate is characterised by a significantly smaller proportion of clay, but a higher proportion of coarse sand and a significantly more alkaline pH and a larger C:N ratio (Fig. 4). Axis 2 clearly separates the Haplic Cambisol from the Technosols and Hyperskeletal Leptosols. At the surface, the transferred soils tend to be closer to the reference steppe soil, in particular those that are not in contact with the phreatic zone (Fig. 3). Significant differences remain, however, in the fine silt and coarse silt content between these two types of soil (Fig. 4). The dispersion of the points corresponding to the Technosols in the NMDS is also much greater than that of the other soils, reflecting a high degree of heterogeneity of the physical and chemical characteristics of this series of soils according to the type of deposition (Fig. 3). With regard to the coarse fragments (> 2mm) present in the topsoils, the Hyperskeletal Leptosols have almost twice the cover of stones and rocks in comparison with all the other types of soil (Kruskal-Wallis: chi-squared = 38.72, df = 5, p-value <0.05***) (Fig. 4).

Soils also differ in their physic-chemical properties. Technosols and hyperskeletal Leptosols contain significantly higher concentrations of CaCO₃ (Kruskal-Wallis: chi-squared = 19.88, df = 5, p-value <0.01**), Ca (F_{5,23} = 5.20, p-value <0.01**) and higher C:N (Kruskal-Wallis: chi-squared = 17.98, df = 5, p-value <0.01**) than other soils (Fig.4). There is no significant difference for the organic matter content (Kruskal-Wallis: chi-squared = 3.89, df = 5, p-value = 0.5654), but Technosols tend to have a higher amount of organic matter than other soils (Figure 4). There were also no significant differences for total nitrogen (Kruskal-Wallis: chi-squared = 6.05, df = 5, p-value = 0.30), Cation Exchange Capacity (Kruskal-Wallis: chi-squared = 10.56, df = 5, p-value = 0.06), plant available P (Kruskal-Wallis: chi-squared = 6.83, df = 5, p-value = 0.23), K (F_{5,23} = 1.42, p-value = 0.25) and exchangeable K (F_{5,23} = 1.43, p-value = 0.25)



367
368
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370
371

Fig. 3: Range of two important variables (Clay (g/kg) and pH water ratio 1:5) in the NMDS performed on the 29 soil analyses for the 6 types of soil (NMDS stress: 0.045). The coloured curves represent the values of the two variables studied: clay (red) and pH (green).



372

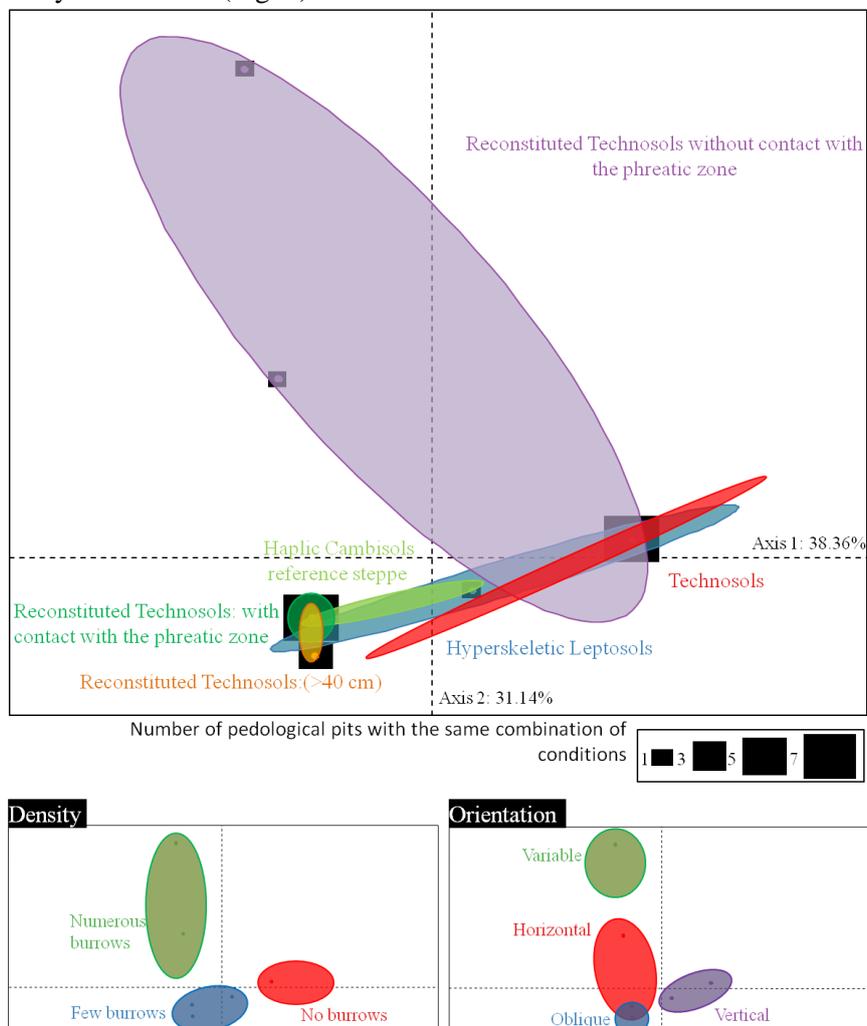
373 Fig. 4: Means and standard error of the different variables studied for each type of soil from the
 374 quarries and the steppe (N = 4 or 5). The bars of the histogram with letters in common are not
 375 significantly different according to the post-hoc comparisons Tukey HSD tests or Wilcoxon tests with
 376 Bonferroni adjustment.

377

378 3.3. Relation between type of soil and traces of biological activity

379 3.3.1. Earthworm activity

380 Axis 1 (38.36% of inertia) of the MCA performed on the data for presence of earthworms
 381 discriminates the soil transfers (reconstituted Technosols) without contact with the phreatic zone from
 382 other types of soil (Fig. 5). Soils with no contact with the phreatic zones have an organization similar
 383 to that of the original ecosystem but with a higher level of earthworm activity, evidenced by the
 384 presence of numerous burrows running in all directions. The other soil transfers show signs of the
 385 presence of earthworms but in lower proportions, like in the steppe. They are characterised by the
 386 small number of tunnels, mainly nondescript or oblique, reflecting changes in the macrostructure of
 387 the soils and / or the distribution of coarse fragments. Hyperskeletal Leptosols and Technosols do not
 388 present or have very few tunnels (Fig. 5).

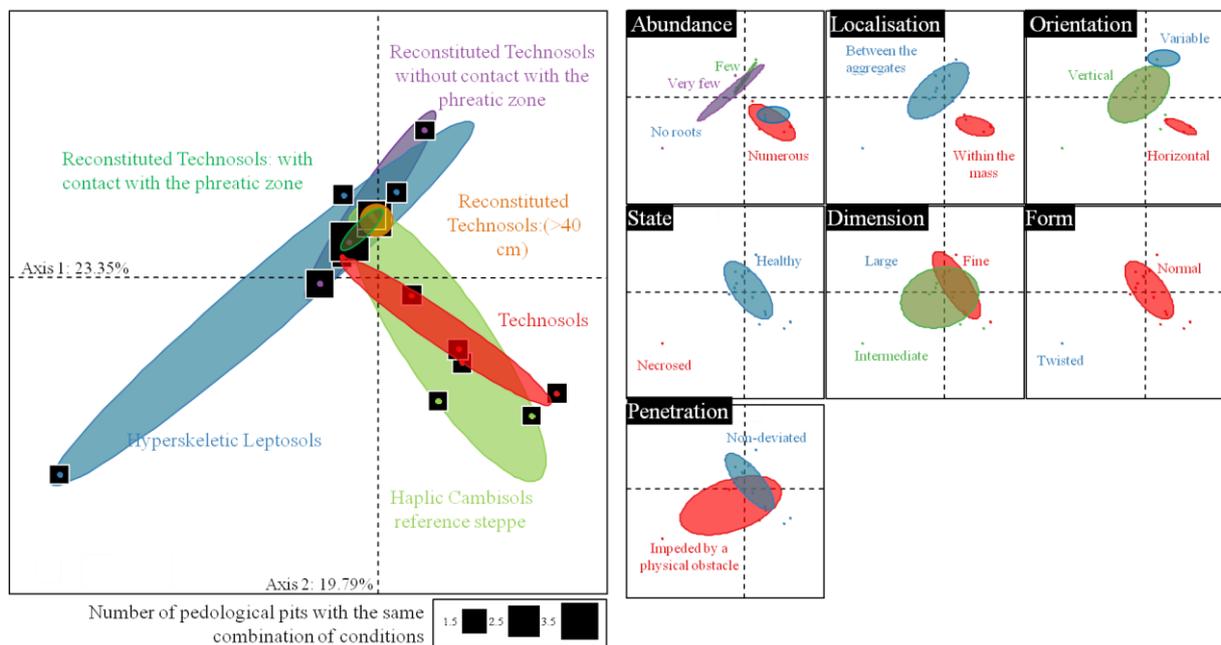


389 Fig. 5: MCA on the different types of soil with projection of the signs of presence of earthworms (6
 390 types of soil × 19 descriptions of soil profiles).
 391

392

393 3.3.2. Root activity

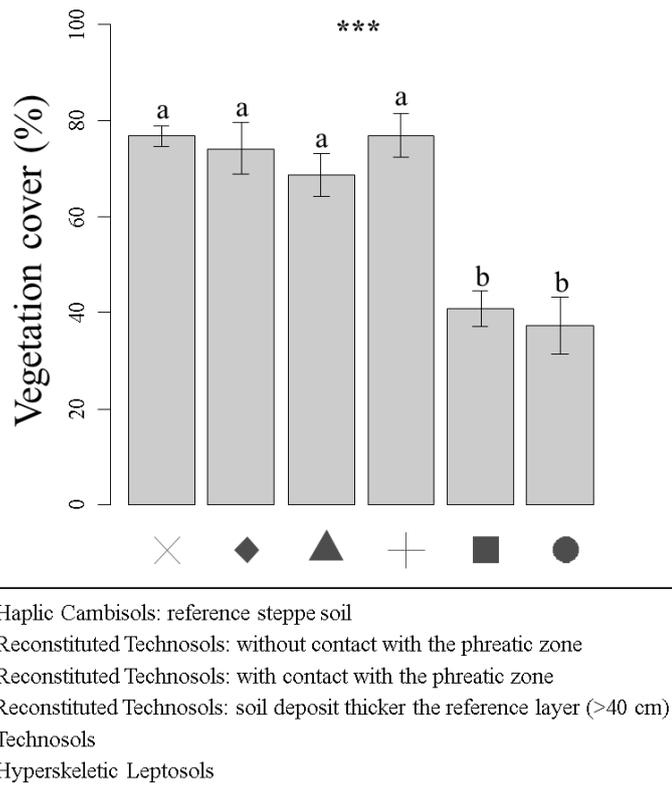
394 In the Multiple Component Analysis (MCA), Axis 1 (23.35% of inertia), clearly separates the soil
 395 transfers from the Technosols (Fig. 6). In contrast, Axis 2 (19.79% of inertia) discriminates the
 396 Technosols from the Hyperskeletic Leptosols. The Technosols present a very small quantity of roots,
 397 or even their absence. The small, fine roots have a mainly nondescript orientation. The Hyperskeletic
 398 Leptosols present very few roots. They are of intermediate size and vertical orientation. The majority
 399 of these roots are also impeded by a physical obstacle resulting in twisted roots compared to those of
 400 other soils.
 401 Soils where there was a transfer and whatever the mode (with or without contact with the water table,
 402 > 40 cm of sol), present the greatest number of roots of variable or vertical orientation. The roots are
 403 healthy and of all sizes (fine, intermediate or large roots) present within the same profile. Finally,
 404 these roots deviate very little. The steppe is characterised by a high abundance of intermediate-sized
 405 roots, and most often impeded by a physical obstacle owing to the high proportion of pebbles in these
 406 soils. These characteristics are also found in the three types of soil transfer (Fig. 6).
 407



408
 409 Fig. 6: MCA on the different types of soil with projection of the characteristics of the root activity (6
 410 types de soils × 19 descriptions of soil profiles).
 411

412 3.4. Soil and plant cover relation

413 The plant cover differs significantly in the different types of soil in the quarries (Kruskal-Wallis: chi-
 414 squared = 55.65, df = 5, p-value <0.05***) (Fig. 7). All the soil transfers are similar to the steppe
 415 Cambisol, with more than 60% of plant cover on average per quadrat. In contrast, the Technosols and
 416 the Hyperskeletic Leptosols, which do not differ significantly from each other, present more than half
 417 as much plant cover in comparison with the other types of soil.
 418



419 Fig. 7: Vegetation percent cover studied for each type of soil from the quarries and the steppe (N = 4
 420 or 5). The bars of the histogram with letters in common are not significantly different according to the
 421 post-hoc comparisons Wilcoxon tests with Bonferroni adjustment.
 422
 423

424 4. Discussion

425 It has already been demonstrated that opencast mining entails a high level of variability of the soils
 426 (Dimitrakopoulos and Mackie, 2008). The various techniques of excavation and restoration of the sites
 427 also give rise to marked heterogeneity in the development of soil biota and vegetation (Chenot et al.,
 428 2017; Frouz et al., 2001). Our results confirm that all the soils resulting from the former operation of
 429 the quarries present their own specific characteristics but which remain very remote, even in the very
 430 long term, from the characteristics of the destroyed Haplic Cambisol (Hyperskeletal Leptosols,
 431 Technosols). Pedogenetic processes are very slow or even blocked by the recurrent action of certain
 432 environmental parameters (random fluctuation of the water table subjected to artificial irrigation
 433 processes in the plain evidenced by observations of hydromorphic stains in soils). The soil transfer
 434 operations undertaken under good conditions (same soil thickness as the reference steppe and no
 435 contact with the phreatic zone) have on the other hand made possible to restore all the physical and
 436 chemical properties recorded in the reference steppe soil in the topsoil (0-40 cm) except for the fine
 437 and coarse silt content, and for earthworm and root activity.
 438

439 The original soil of the areas degraded by the quarries is usually lost in part or totally, leaving only
 440 skeletal materials (Kundu and Ghose, 1997; Sheoran et al., 2010; Wong, 2003). In our case, the Haplic
 441 Cambisol was replaced by raw geological material, the Durancian pebble on which the Hyperskeletal
 442 Leptosols develop, reflecting above all the properties of the outcropping bedrock. It is associated with
 443 a loss of the basic structural elements, often with a lack of organic matter and the associated nutrients
 444 (Harris et al., 1998) and marked by the strong presence of coarse fragments (>60%) (Baize and Girard,
 445 2008), as evidenced by our results.
 446

447 In the absence of rehabilitation of these sites after mining ceased, these Hyperskeletal Leptosols
448 persist, and 30 years after their abandonment, very few of these soils have evolved towards soils with
449 a more complex organisation. A beginning of pedogenesis over a few centimetres at the surface was
450 observed following the deposition of leaves at the most heavily wooded sites, in particular by poplars
451 that have become established there. The pedogenetic processes may also be blocked in these soils
452 following the artificial fluctuations of the water table zone itself, associated with the sampling and
453 restitution of waters in relation with the irrigation systems of the fruit orchards (drop by drop) and the
454 hay meadows of La Crau (submersion) (Beltrando, 2015). The shallow depth of the Hyperskeletal
455 Leptosols associated with a harsh pedoclimate, which can be very dry in summer, and the high
456 concentration of pebbles (Jim, 2001) are also a constraint on the root volume of plants, which is thus
457 very limited. The absence of fine particles associated with the domination of dilated pores present in
458 the sandy matrix limit the retention of water necessary to the plants when they are no longer in contact
459 with the phreatic zone. The virtual absence of earthworms and roots in these soils makes them very
460 impoverished and lacking structure and in consequence of poor quality (Hu et al., 1992; Sheoran et al.,
461 2010). In addition, these soils, because of their pseudo-soft consistency and their sandy texture, are
462 very sensitive to erosion and their fine particles may thus be regularly wind eroded by the strong
463 presence of the *Mistral* in this region (Devaux et al., 1983). With regard to the chemical parameters,
464 these soils are also very poorly fertile. The cation exchange capacity and the stocks of essential plant
465 nutrients, in particular nitrogen and phosphorus, are low. These conditions constrain the plant
466 development, and this explains why very low herbaceous plant covers were observed. Even after 30
467 years of quarry abandonment, these soils remain very remote from the reference Haplic Cambisol and
468 there is no indication to suggest that there might one day be a progression towards this type of soil,
469 given the extent of the degradation (suppression of the fersialitic layer) and the new environmental
470 conditions generated by mining (destruction of the conglomerate and intermittent contact with the
471 phreatic zone, depending on the depth of the quarrying).

472
473 These new environmental conditions entail problems with regard to the development and the
474 maintenance of the vegetation at the formerly exploited sites (low plant cover and root activity). The
475 plant cover which develops there has only limited access to nutrients, in particular during periods of
476 drought. The establishment of the vegetation is slow and develops with difficulty, thus limiting the
477 ecological succession, leaving the ecosystem at a pioneer stage (small biomass and rare nutrient
478 content), rather characterised by dry grasslands (Harris et al., 1998; Tomlinson et al., 2008; Walker
479 and Moral, 2003; Wong, 2003). Yuan et al. (2006) have shown that this is more marked by the limited
480 volume of the available soil than by the fertility of the soils. These Hyperskeletal Leptosols are thus
481 considered of poor quality at the agronomic level (Hu et al., 1992; Sheoran et al., 2010). However, at
482 the biological level, many of these habitats are classified as of interest by the European Community
483 (priority habitats according to the European directive), because of the presence of rare species (Baize
484 and Girard, 2008).

485
486 After mining ceased, and mainly for safety or landscaping purposes, various rehabilitation measures
487 were undertaken at these sites. They mainly consisted in depositing a wide variety of materials on the
488 Durancian pebbles. They resulted in the development of Technosols when they developed on non-
489 pedological transported materials (mine or quarry spoil, domestic waste, residual sludge, slag, rubble,
490 concrete, asphalt, *etc.*) (Baize and Girard, 2008). The physical and chemical properties of these soils
491 are thus highly heterogeneous and far removed from the reference Haplic Cambisol, as is the
492 vegetation that develops there (poplar or willow forests, wetland water meadows, *etc.*). As on the
493 Hyperskeletal Leptosols, little vegetation develops because of the quality of the materials and the
494 compacting caused by the heavy equipment that deposited these materials. This compacting results in

495 a loss of soil structure, limits the presence of earthworms, and the development and penetration of
496 roots. Nevertheless, given the more or less distant origin of the materials deposited at the site, the
497 vegetation developing there may be composed of species that are rare at the regional scale (Chenot et
498 al., 2017) and may thus possess a heritage value that should be taken into account in possible future
499 redevelopment planning. In contrast to the Hyperskeletal Leptosols, the dumping of these materials
500 has nonetheless led to the insulation of the topsoil from fluctuations in the water table, giving rise to
501 the development of more xeric soils.

502
503 In other cases, there has been rehabilitation with the dumping of soil transfers. These deposits are
504 constituted of fersialitic layers from the arable layers of the site before the start of exploitation, but
505 mixed with each other or with other materials derived from the quarrying (*poudingue* blocks,
506 decantation clays, various kinds of rubble, etc.). This results in reconstituted Technosols. This
507 rehabilitation process involves the succession of various operations: the removal of the surface layers
508 (< 40 cm) down to the puddingstone, its stockpiling, its storage for a variable period of time
509 corresponding to the time of the destruction of the underlying puddingstone and the extraction of the
510 Durancian pebbles (5 to 10 years), its transport and finally its re-spreading at the chosen site. Each of
511 these operations may involve a certain degradation of the physical properties, in particular the leaching
512 of certain fine particles such as the silt in the present case. The structure of the soil may also be
513 degraded, the reduced porosity resulting in poor aeration of the soil, poor drainage and increased
514 resistance to the penetration of roots, which in consequence reduces the plant growth (Baize and
515 Girard, 2008; Bowen et al., 2005; Geissen et al., 2013; Stahl et al., 2002).

516
517 This study clearly shows the wide diversity of the soils that have been deposited or have according to
518 the different types of exploitation and rehabilitation been undertaken formerly. If the positive impact
519 of the diversity of certain modes of quarrying have already been demonstrated with regard to the flora
520 (Chenot et al., 2017; Craig et al., 2015; Prach et al., 2013; Vécirin and Muller, 2003), and the fauna
521 (Adamopoulou and Legakis, 2006), few studies have focused on the impact on the diversity of the
522 soils developed relative to the original situation (Jarvis and Walton, 2012).

523
524 Thirty years after the rehabilitation process, the reconstituted Technosols present little significant
525 difference with the reference steppe, whatever the physical or chemical parameter measured. They
526 may therefore be characterised as of much better quality for the rehabilitation of the pre-existing
527 steppe type vegetation compared to the Technosols and the Hyperskeletal Leptosols, and in particular
528 for the soil transfer carried out on substrates allowing no contact with the phreatic zone (Chenot et al.,
529 2017). The transferred fersialitic layers present better water retention characteristics than the
530 Hyperskeletal Leptosols or Technosols because of the much lower stone content and the presence of
531 particles of less than 2 mm which improve them (Moreno-de las Heras et al., 2008; Nicolau, 2002;
532 Sheoran et al., 2010). These characteristics allow a better development of the vegetation in these soils.
533 Plant cover of more than 80% has been recorded on these soils as well as extensive root development.
534 The soil transfers thus allow a much faster improvement of the topsoil, in particular due to the earlier
535 establishment of the vegetation (Bulot et al., 2014; Weber et al., 2015) compared to the Hyperskeletal
536 Leptosols. Consequently, the reconstituted Technosols are much closer to the reference soil, at least
537 regarding the topsoil, confirming the results obtained in the short term by Bulot et al. (2017). It has
538 however already been demonstrated in the La Crau plain that the soil transfer had an impact on the
539 content of total nitrogen, organic carbon and the pH, but only in the short term (3 years) (Bulot et al.,
540 2014, 2017). The time that has passed since the rehabilitation may therefore explain the absence of
541 significant differences 30 years after the re-spreading of the soil.

542

543 Similarly, the plant cover in the reconstituted Technosols is similar to that of the reference steppe.
544 However, the plant communities are not similar with regard to their specific composition and their
545 structure (Chenot et al., 2017). This might in particular be explained by the non-reestablishment of the
546 whole process of coexistence which governs the structuring of the steppe communities resulting from
547 several thousands of years of sheep grazing and rangeland fires (Henry et al., 2010), but also the not
548 yet differentiated activity of the soil fauna, of which the strong influence on the composition of the
549 vegetation has already been demonstrated (De Deyn et al., 2003). The transferred soils without contact
550 with water thus show more intensive earthworm activity than the other types of transfer. The density
551 of the galleries is much lower in the soils subjected to the fluctuations of the water table
552 (Hyperskeletal Leptosols), constituted of anthropogenic materials (Technosols) or with the deposition
553 of more than 40 cm of earth (Boyer et al., 2011; Geissen et al., 2013). The low earthworm density
554 might thus contribute to the limitation of the development of the plant cover (Frouz et al., 2007;
555 Scullion and Malik, 2000). The presence of earthworms, acting on the soil structure, allows the plants
556 to benefit from more extensive root development and favours access to water and nutrients (Boyer and
557 Wratten, 2010).

558

559 Nowadays, the rehabilitation of quarries after the end of exploitation is compulsory (UNEP et al.,
560 2005; UNEP/CBD/COP, 2012). The natural recovery of a site is a long process and it has sometimes
561 been recommended to wait a certain time (several hundred years) studying the natural dynamics before
562 adopting management measures if sites are to be rehabilitated (Letheren, 2009; Rao et al., 2000).
563 However, spontaneous restoration is not foreseeable in the context of global change. It is therefore not
564 considered an acceptable rehabilitation strategy (Cullen et al., 1998). For the rehabilitation of
565 ecosystems and of the ecological functions in a post-mining landscape, reconstructing soils is thus
566 necessary (Jim, 2001). Soil engineering operations should therefore be undertaken (Bradshaw, 1997),
567 except for some specific ecosystems where the question arises whether ecological rehabilitation is
568 really necessary. The formation of the topsoil, that is the organo-mineral layers, affected by the
569 vegetation (source of organic matter) and by the biota of the soil (which transforms the organic
570 matter), is of particular importance. The reconstitution and the management of a layer of soil suited to
571 supporting the vegetation in the long term is thus a crucial phase of ecological rehabilitation. The soil
572 component as limiting factor may frustrate attempts at restoration (Bulot et al., 2017; Jim, 2001).

573

574 The most widely used technique and which is considered as the best for rehabilitating the reference
575 ecosystem is soil transfer (Bulot et al., 2017; Fowler et al., 2015). Our results show that in the long
576 term, the replacement of the topsoil by transfer presents characteristics that are virtually similar to
577 those of the steppe topsoil. It is thus a very important operation to take into account for the
578 management of sites post-mining. This technique should be very carefully studied before putting it
579 into operation (depth of excavation, height and duration of stockpiling, conditions of re-spreading,
580 etc.). Serious damage may be done to the soils if they are improperly managed during their
581 reestablishment post-mining (Geissen et al., 2013; Park et al., 2011; Strohmayer, 1999). The main
582 problems likely to occur are the loss of soil structure and excessive compacting (Duncan and
583 Bransden, 1986; Ghose, 2001). This damage may be caused to the soil if the topsoil is removed under
584 humid conditions, or if heavy vehicles are driven over the soil after re-spreading. Even if the
585 replacement of the topsoil would appear to be the best way to rehabilitate mine ecosystems (Fowler et
586 al., 2015; Ghose, 2001; Vécirin and Muller, 2003), various other rehabilitation measures may be
587 proposed. In particular, in the case of absence of original vegetal earth and the excessive cost of
588 importing vegetal earth from elsewhere. In other cases, the topsoil may have lost all its properties and
589 its seed banks when it has been stockpiled for too long and is responsible for the development of
590 weeds which have been trapped by the heaps of soil during stockpiling (Golos and Dixon, 2014;

591 Jefferson and Usher, 1987; Jones and Esler, 2004). In these cases, debris may even be preferable to the
592 topsoil. For this process, it is recommended to use species adapted to the constraints of the soils and
593 which could colonise them. It has been shown that it is essentially the rapidly developing mycorrhiza
594 and / or nitrogen-fixing species directly sown or planted on the bare substrate that will speed up the
595 pedogenesis of the soils (Bellingham et al., 2001; Brune et al., 2007; Meuser, 2012) and enable the
596 implantation of the desired species (Callaway, 1997, 1995). It has been shown that these species allow
597 an increase in the carbon and nitrogen content of the soil after their installation (Macedo et al., 2008),
598 which would enhance the quality of the soil and put the ecosystem back on the right track towards the
599 reference ecosystem. The choice of species may also focus on the fast-growing pioneer species, giving
600 priority to native species (Bellingham et al., 2001; Parrotta et al., 1997). There is a wide range of
601 rehabilitation recommendations, and it is important to carry out a full analysis of the ecosystem before
602 attempting the rehabilitation of the sites, integrating in particular the description of the soils
603 developed. It should not be overlooked that the ecosystems have a certain resilience and may restore
604 themselves, without human intervention (Bradshaw, 1997). Similarly, active restoration operations
605 (here, soil transfer) should also be assessed in the short term (Bulot et al., 2014, 2017) but also in the
606 very long term in order to integrate the slow pedogenetic processes.

607

608 **Conclusions**

609 This study confirms that all the soils resulting from the former exploitation modes and rehabilitation of
610 the quarries present their own specific characteristics (upper soil layer fertility, soil profile vertical
611 organization). Moreover they remain very different, even after 30 years, from the characteristics of the
612 Haplic Cambisol of the destroyed reference soil ecosystem. Pedogenetic processes are very slow or
613 even blocked by the recurrent action of some environmental parameters such as the artificial and
614 random fluctuation of the water table. In terms of ecological rehabilitation, only topsoil transfers have
615 allowed to restore most of the physical and chemical properties recorded close to the reference
616 ecosystem soil but only in the soil upper-layer. Nevertheless, this technique must be used in good
617 conditions to reach the restoration objectives: no long topsoil stockpiling, topsoil manipulation in dry
618 conditions, etc.. Soil study is then an indispensable step to understand ecosystem functioning and to
619 optimize ecological rehabilitation efficiency.

620

621 **Acknowledgements**

622 This study was supported by funding from the company Gagneraud Construction. We thank the
623 *Réserve Naturelle Nationale des Coussous de Crau* and the *Grand Port Maritime de Marseille* at Fos-
624 sur-Mer for permission to access the study sites. We thank Pierre Bourguet and Jean-Marc Arnal
625 (*Société des Carrières de La Ménéduelle*) for their collaboration with regard to the early exploitation of
626 quarries. We are also grateful to our PhD students and our technician for assistance with the field
627 work, analyses and general reflection: Anne Aurière, Cannelle Moinardeau, Hervé Ramone.

628

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878 Appendix A. Modes and factors measured for the traces of animal and plant biological activity in the
 879 20 profiles describe (Falipou and Legros, 2002)
 880

Biological compartment studied	Modes	Factors
Earthworms	Density	- No burrows - Few burrows (1-3/dm ²) - Numerous burrows (3-5/dm ²) - Very numerous burrows (>5/dm ²)
	Orientation	- Vertical - Layertal - Oblique - Variable
Roots	Abundance	- No roots - Very few (<8/dm ²) - Few (8-16/dm ²) - Numerous (16-32/dm ²) - Very numerous (>32/dm ²)
	Localisation	- Within the mass - In the aggregates - Between the aggregates - In the crevices - Avoiding compacted zones
	Orientation	- Vertical - Nondescript - Oblique - Variable
	State	- Healthy - Necrosed - Rotten - Rust-stained
	Dimension	- Very fine (<0.5 mm) - Fine (0.5 to 2 mm) - Intermediate (2 to 5 mm) - Large (5 to 20 mm) - Very large (> 20 mm)
	Form	- Normal - Twisted - Fishbone - Flat - Change of direction
	Penetration	- Non-deviated - Impeded by a physical obstacle - Impeded by a chemical obstacle

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